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FINAL REPORT

CONTRACT NAS-3-9439

17 March 1967 to 17 December 1969

GENERATION OF LONG TIME CREEP DATA ON REFRACTORY ALLOYS AT ELEVATED TEMPERATURES

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15 January 1970

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FOREWORD

The work described herein was performed by TRW Inc. under the sponsorship of the National Aeronautics and Space Administration under Contract NAS-3-9439. The period of performance on this contract was March 17, 1967 to December 16, 1969. This contract is a continuation of work initiated under Contract NAS-3-2545 which covered the period from June 26, 1963 to March 16, 1967. The purpose of both contracts was to obtain design creep data on refractory metal alloys for use in advanced space power systems. A listing of all reports prepared on both programs is included in Appendix I.

The program is administered for TRW Inc. by Dr. E. A. Steigerwald, Program Manager; Dr. K. D. Sheffler is the Principal Investigator with Mr. R. R. Ebert contributing to the program. The NASA Technical Manager is Mr. P. E. Moorhead.

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ABSTRACT

Ultrahigh vacuum (<10^{-8} torr) creep test data are reported for W-25%Re alloy, for the molybdenum base alloys TZC and TZM, for pure tantalum, and for the tantalum base alloys T-111, Ta-10W, and ASTAR 811C. The parameters used to characterize creep behavior were the 1/2% or 1% creep life, although creep rates were also used in some cases. Test conditions were generally chosen to provide creep lives between 5000 and 20,000 hours. Individual creep curves are presented for each test, and life data are summarized on Larson-Miller plots.

Results are also presented from tests on T-111 alloy with continuously varying loads and temperatures. Analysis of these results indicated that creep behavior under these conditions can be related analytically to conventional constant temperature, constant load test results for this alloy. In addition, results are reported from an extensive study of the elevated temperature mechanical behavior of T-111 alloy and from a study of the influence of heat treatment on the creep behavior of ASTAR 811C alloy. The T-111 study involved an investigation of the interactions between creep and strain aging behavior and also a mathematical analysis of creep rates. The results indicated that strain aging strengthening due to oxygen can be an effective mechanism for retarding creep in T-111 alloys. As a result the loss of oxygen which can occur in ultrahigh vacuum environments can lead to a significant increase in creep rate with an increasing exposure time.

Results of the study on ASTAR 811C revealed a significant influence of heat treatment on the creep of this alloy, with specimens annealed for very long times or at very high temperatures having significantly better strength. It is believed that both grain size and carbide morphology contribute to these effects.

SUMMARY

Tests were conducted on molybdenum-base alloys, TZC and TZM to determine the influence of heat treatment and processing variation on creep behavior. Both alloys showed significant property variations as a function of processing history. In the lower stress range, the creep resistance of these two materials in the stress-relieved condition was comparable. However, a special heat of TZM containing a higher than normal carbon content and processed at relatively high temperatures was superior to the TZC in the higher stress range. A limited number of tests conducted on Ta-10W alloy indicated that this material had a creep strength comparable to T-111.

Extensive evaluations were conducted on the creep behavior of tantalum-base alloys and the effects produced by variations in microstructure and testing parameters. In pure tantalum fine grain size improved creep strength at test temperatures below 1350°F (932°C). This effect was particularly evident in the rapid creep that occurred in the heat affected zone of welds where the thermal history produced a relatively large grain structure. In the T-111 alloy, creep strength data suitable for design applications were obtained over a range of stresses and temperatures. An analysis of tension test results obtained on the T-111 material indicated that significant strengthening occurred in the 1600°F (870°C) temperature range as a result of strain aging produced by oxygen. The significantly decreased creep rate which was observed in this temperature region could also be attributed to the strain aging effect. At relatively long test times (>1000 hours) the ultrahigh vacuum environment (10^{-9} torr) caused a depletion in the oxygen content of the test sample. As a result the strain age strengthening mechanism was removed and an increased creep rate was observed. An analysis of the steady state creep rates in T-111 provided values for the activation energy and stress exponent.

A limited number of tests conducted on Ta-10W alloy indicated that this material had a creep strength comparable to T-111.

In order to characterize the creep behavior of T-111 alloy for radioisotope capsule applications, a study was made of creep in T-111 alloy under the influence of increasing loads and decreasing temperatures. Results showed that the creep rate under these test-conditions varied continuously with time, and in most cases the instantaneous rates in the variable tests were comparable to isostatic, isothermal steady state creep rates at equivalent stress and temperature levels. This correspondence of strain rates was used to develop a technique for predicting the variable stress and temperature creep life of T-111 alloy from conventional test data. The analytical treatments developed from these comparisons were then used as guidelines for analytical studies of the variable stress and temperature creep behavior of a 316 stainless steel and an Inconel 718 alloy.

Creep tests were conducted on the tantalum-base alloy ASTAR 811C to provide design data and to determine the influence of heat treatment on creep strength. Commercially-produced ASTAR was significantly stronger than laboratory heats of this material. The creep strength was dependent on both grain size and carbide morphology, with larger grain sizes providing improved creep resistance.

A W-25%Re alloy which is being considered for a high temperature bellows application was tested to determine the temperature and stress limits for prevention of creep extension. Results showed that at 10 ksi (68.9 MN/m^2) the alloy will not exhibit significant creep ($<1 \times 10^{-7}$ in 200 hours) below 1800°F (982°C), while at 15 ksi (104 MN/m^2) measurable creep ($>1 \times 10^{-7}$ in 200 hours) would occur at or above 1700°F (927°C).

INTRODUCTION

High temperature creep represents a potential material limitation in the design of space electric power systems. It is therefore necessary to characterize the creep behavior of the various refractory alloys which are candidates for the fabrication of space power system hardware. These components will operate either in the vacuum of outer space or in liquid-metal environments where the concentration of reactive species is extremely low. Because of this and the well known sensitivity of refractory alloys to interstitial contamination, it is necessary to conduct creep tests in a non-contaminating environment in order to obtain representative design data. The present program was thus undertaken to generate design creep data on refractory alloys in the ultrahigh vacuum ($<10^{-8}$ torr) environment. The specific refractory alloys tested under this program were W-25%Re, TZC, TZM, pure tantalum, T-111, Ta-10W and ASTAR 811C. The creep parameter selected for design characterization was the time required to reach 1/2% or 1% permanent plastic strain. Creep test conditions were normally selected to provide creep lives between 5000 and 20,000 hours.

Although the basic purpose of the creep program was the generation of design data on refractory alloys in ultrahigh vacuum, proper implementation of this objective necessarily involved several supplemental studies concerning details of the high temperature mechanical behavior of the refractory alloys tested. One of these studies involved an extensive investigation of the elevated temperature tensile and creep behavior of T-111 alloy, including a study of creep under the influence of continuously varying loads and temperatures. Additional studies were concerned with the relationships between creep behavior, processing history and microstructure in TZC and TZM alloys, in pure tantalum, and in ASTAR 811C alloy. Detailed discussions of these studies have been published as separate topical reports under this program (see Appendix I) and also in the literature (1,2). The purpose of this final report is to provide a detailed review of the previously published results along with a complete presentation of the design creep data.

II EXPERIMENTAL DETAILS

1. Creep Test Procedures

The creep program involved testing refractory alloys at temperatures ranging from 900 to 3200°F (482 to 1760°C) at stresses between 500 and 65,000 psi (3.4 to 448 MN/m^2). A combination of parameters was generally selected which would provide 1% total creep in 5000 to 20,000 hours. Two-inch gauge length, button-head bar-type specimens and double-shoulder, pin loaded, sheet-type specimens were used respectively for testing of plate and sheet-type materials. The orientation of the specimen with respect to the working direction is given below:

Material Form	Specimen Axis Parallel to
Disc Forging	Radius
Plate	Extruding or Rolling Direction*
Sheet and Strip	Rolling Direction*
Tubing	Tube Axis

* Except where indicated otherwise

The tubing was stressed parallel to the tube axis, with two flats being ground opposite one another to provide two webs in the gauge section.

Both construction and operation of the ultrahigh vacuum creep test chambers and the service instruments in the laboratory have been described in detail elsewhere (3,4). The creep test procedure involved initial evacuation of the chamber to a pressure of less than 5×10^{-10} torr at room temperature, followed by heating of the test specimen at such a rate that the pressure never rose above 1×10^{-6} torr. Pretest heat treatments were performed in situ, and complete thermal equilibrium of the specimen was insured by a two hour hold at the test temperature prior to load application. Pressure was always below 1×10^{-8} torr during the tests and generally fell into the 10^{-10} torr range as testing proceeded. Specimen extension was determined over a two-inch gauge length with an optical extensometer which measured the distance between two scribed reference marks to an accuracy of ±50 microinches. Creep strains were calculated using the loaded gauge length as the original length. Specimen temperature was established at the beginning of each test using a thermocouple. An optical pyrometer having a precision of ±1F° was calibrated against the thermocouple reading and was then used as the prime temperature reference throughout each test.

The response of T-111 alloy to variable stress conditions was studied by continuously increasing the load at various linear rates, starting at zero stress, while simultaneously measuring creep strain as a function of time. The steadily increasing load was achieved by using a motor driven screw to continuously feed lead shot at a uniform rate into a load pan attached to the bottom of the specimen. The weight of the shot added to the pan was monitored so that the exact load would be known at all times.

Variable temperature creep testing was accomplished by attaching a small motor to the temperature controller. The rate of temperature change was then varied by using a series of cams and relays to regulate the speed of the motor.

2. Characterization of Test Materials

Chemical analyses of each of the materials tested are shown in Table 1 and pertinent details of the processing histories are summarized in Table 2. A brief discussion of each category of test materials is presented below:

a. W-25%Re Alloy

The W-25%Re alloy was tested as 0.030 inch stress relieved sheet obtained from an arc melted ingot. The microstructure of this alloy is presented in Figure 1.

b. Molybdenum Alloys

TZM was evaluated in three forms; bar (Heat 7463), a conventionally processed disc forged at 2200°F (Heat 7502), and a section of another disc which had a higher than normal carbon level and was both hot and warm forged to produce improved creep resistance (Heat KDTZM-1175). All of these heats were evaluated primarily in the stress relieved condition. Photomicrographs of each of the materials (Figure 2) show that the bar material and the conventional forging were relatively fine-grained, while the special forging had a somewhat coarser structure. Electron micrographs of the two disc forgings (Figure 3) show a similar carbide morphology, but with a somewhat higher density of carbides in the higher carbon material.

TZC was also evaluated in three different forms. Two rolled plates were obtained with widely different drafting practices. One plate was given very small reductions on each pass and a high finishing temperature (Heat M-80), while the other was given relatively large reductions and finished at a lower temperature (Heat M-91). The third TZC plate was side forged in the 2400°F range from extruded bar stock (Heat 4345).

Table 1

Chemical Composition of Alloys Being Evaluated in Creep Program (Weight %)

Material	W	Re	Mo	Ta	Hf	C	Ti	Zr	N_2	O_2	H_2	Finished Form
TZM (Heat 7463)			Bal.			.016	.48	.08	1	2	1(2)	5/8" diameter bar
(Heat 7502)			Bal.			.010	.51	.091	100	20	7	Forged disc
(Heat KDTZM-1175)			Bal.			.035	.61	.120	43	34	9	Forged disc
TZC (Heat M-80)			Bal.			.127	1.02	.17	18	41	10	Rolled Plate
(Heat M-91)			Bal.			.113	1.17	.270	34	37	10	Rolled Plate
(Heat 4345)			Bal.			.075	1.19	.16	9	19	2	Forged Plate
T-111 (Heat 70616)	8.5			Bal.	2.3	.0044			20	55	6	Nominal 0.030" sheet
(Heat 65079)	8.7			Bal.	2.3	.0030			50	130	4	Nominal 0.030" sheet
(Heat 65076)	8.6			Bal.	2.3	.0040			20	100	3	Nominal 0.030" sheet
(Heat D-1102)	7.9			Bal.	2.3	.0030			34	20	3	Nominal 0.030" sheet
(Heat D-1670)	7.9			Bal.	2.4	<.0010			20	72	<5	Nominal 0.030" sheet
(Heat D-1183)	8.7			Bal.	2.2	.0036			10	25	6	Nominal 0.030" sheet
(Heat 650028)	8.3			Bal.	2.1	.0030			12	30	1.9	Nominal 0.030" sheet
(Heat 848001)	7.9			Bal.	2.0	.0010			13	21	1	Nominal 0.030" sheet
(Heat 650038	8.6			Bal.	2.0	.0025			20	100	2.8	Nominal 0.600" plate
(Heat 8048)	7.6			Bal.	1.9	.0037			24	34	1.6	Nominal 0.165" strip
ASTAR 811C												
(Heat NASV-20-WS)	7.3	1.0		Bal.	0.86	.0240			20	14		Nominal 0.030" sheet
(Heat VAM-95)	7.6	1.1		Bal.	0.65	.0300			3	4	0.3	Nominal 0.030" sheet
(Heat 650056)	8.2	1.2		Bal.	0.9	.0200			14	30	3.5	Nominal 0.030" sheet
Ta-10W												
(Heat 630002)	9.9			Bal.		.0044			25	100	5	Nominal 0.030" sheet
Pure Tantalum												
(Heat B-1962)				Bal.		.0012			21	20	5	Tubing
(Heat 60249)				Bal.		.0014			20	22	3	Tubing
(Heat 60065)				Bal.		.0015			19	12	5	Tubing
(Heat 60379)				Bal.		.0019			22	15	4	Tubing
(Heat 818072)				Bal.		.0010			19	54	2	2-1/2" plate
(Heat B-1960)				Bal.		.0010			14	48	5	.160" strip
W-25%Re												
(Heat 35-75002)	Bal.	24.88			.52	.0300			17	20	3	Nominal 0.030" sheet

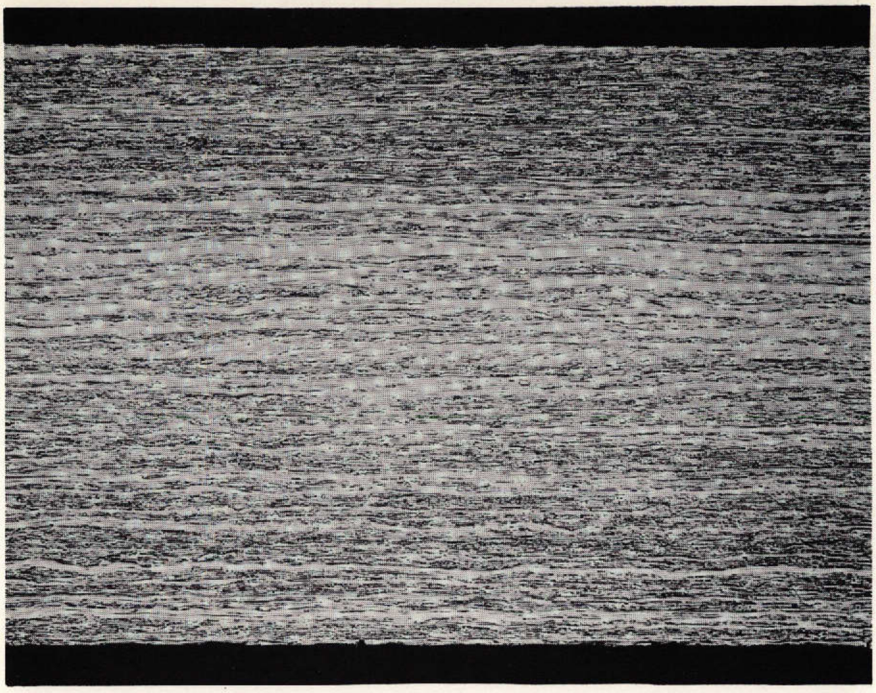
TABLE 2

SUMMARY OF TEST MATERIAL PROPERTIES AND PROCESSING DETAILS

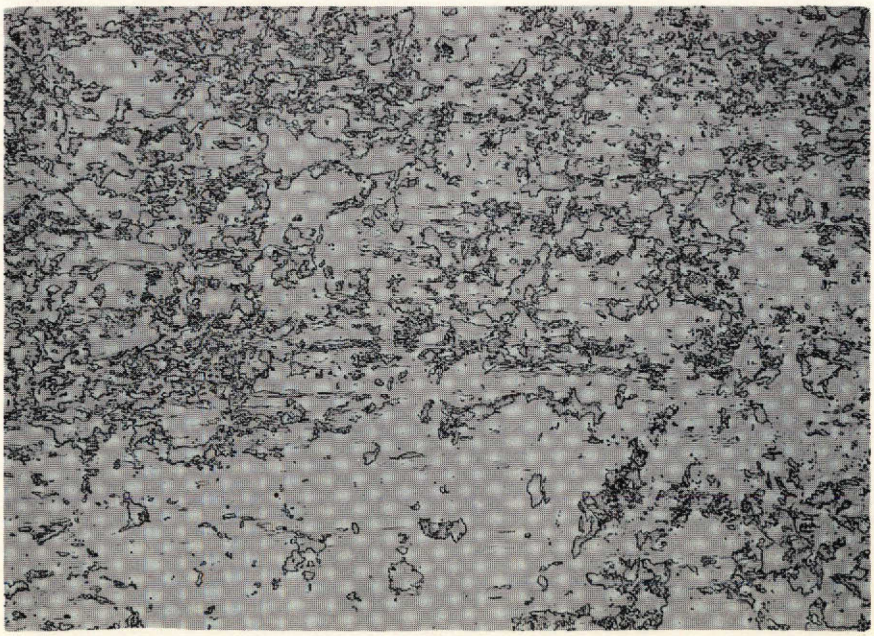
Material	Heat No.	Vendor	Pertinent Processing Details	Heat Treatment	Tensile Strength KSI Ultimate	0.2% Yield	Percent Elongation	DPH Hardness
TZC	M-80	General Electric	Extruded 2.3:1 at 3092°F, Cross-Rolled at 2925°F with 4% Reduction per Pass	3092°F 1 Hour	68.6	68.5	0.05	268
TZC	M-91	General Electric	Extruded 2.3:1 at 3092°F, Cross-Rolled with large deformations per pass and finished at 2372°F	3092°F 1 Hour	85.0	49.0	7.0	240
				2500°F 1 Hour	106	99	4	303
TZC	4345	Climax Molybdenum	Extruded at 3000°F, Heat Treat 3000°F, Upset Forged 40% at 2400°F, Broad Forged to 0.825" at 2400°F	2400°F 1 Hour	123	117	12	346
TZM	7502	Climax Molybdunum	Extrude from 10 3/4" to 6 1/4" dia. Heat Treat 2700°F Upset Forge at 2200°F	2200°F 1 Hour	--	--	--	304
				2850°F 1 Hour	--	--	--	209
TZM	KDTZM 1175	Air Research-Universal Cyclops	Extrude 10 3/4" to 6 1/4" dia. Recrystallize 2800°F 4 Hr. Forge to 4" dia. 3400°F to 2800°F, Recrystallize 2950°F 2 Hr. Forge to 3/4" flat disc, 11 Blows, 2800°F to 2160°F	2300°F 1 Hour	122	111	17.4	316
TZM	7463	Climax Molybdenum	Extrude to 11 1/2" to 6 1/2" dia. Recrystallize, Roll to 2" dia. Recrystallize, Roll to 1" dia. Swage to 5/8" dia.	2250°F 1/2 Hour	128	117	30	300

TABLE 2 (continued)

Material	Heat No.	Vendor	Pertinent Processing Details	Heat Treatment	Tensile Strength KSI Ultimate	Tensile Strength KSI 0.2% Yield	Percent Elongation	DPH Hardness
W-25%Re	3.5-75002	Wah Chang	Stress Relieve 0.055" Sheet 2375°F, Roll to 0.035", Stress Relieve 2550°F	-	-	-	-	639
T-111	Typical	Wah Chang	Forge 6 1/2" dia. ingot to 1 1/2" bar at 2200°F anneal 3000°F, Roll 800°F to 1/4' thick anneal 3000°F, cold roll to 0.030"	3000°F 1 Hour	94	TYPICAL 74	35	250
T-111	Typical	Fansteel	Extrude 3.25:1 at 2200°F, Rod Roll and Flat Roll to 0.030"	3000°F 1 Hour				
Pure Ta			Double e.b. melt extrude 2" O.D. x 1/4" wall tube reduce and draw to 3/4" O.D. x 0.040" wall	-	-	-	-	
ASTAR 811C	Typical	Westinghouse	Side forge 3.9" dia. x 5" long ingot to 7.2" x 7.5" x 1.133" thick bar at 2550°F; anneal 2700°F 2 hr., Roll to 1/4" at 500°F anneal 1 hr. 3000°F; cold roll to 0.040"	-	-	-	-	253



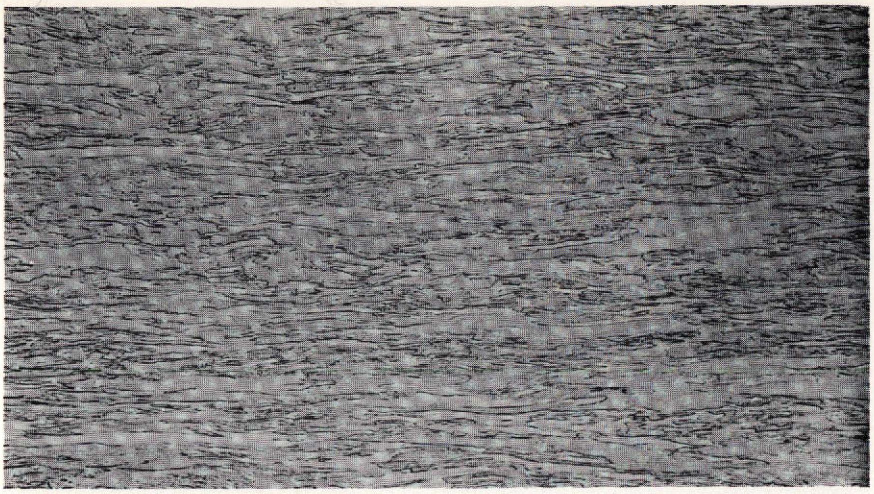
EDGE PERPENDICULAR TO ROLLING DIRECTION



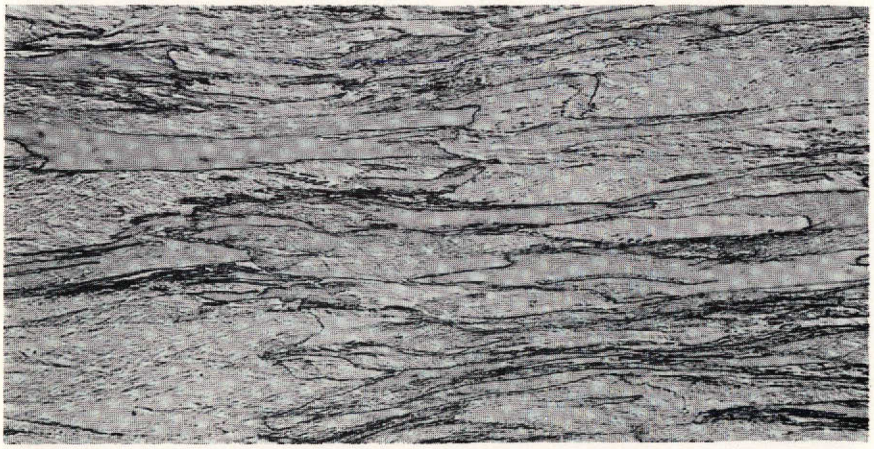
SURFACE OF SHEET

FIGURE 1. MICROSTRUCTURE OF STRESS RELIEVED TUNGSTEN-25% RHENIUM ALLOY SHEET (HEAT 3.5-75002).

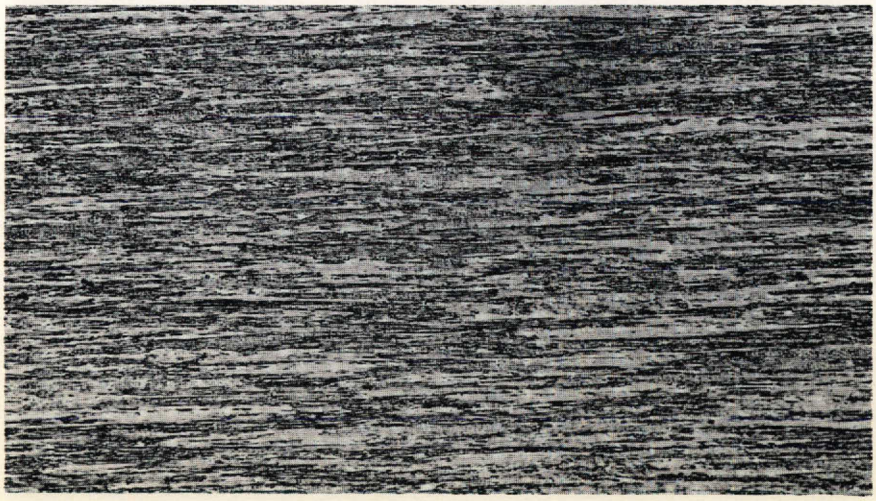
7665



CONVENTIONALLY PROCESSED TZM DISC FORGING (HEAT 7502)
EDGE PERPENDICULAR TO RADIAL DIRECTION

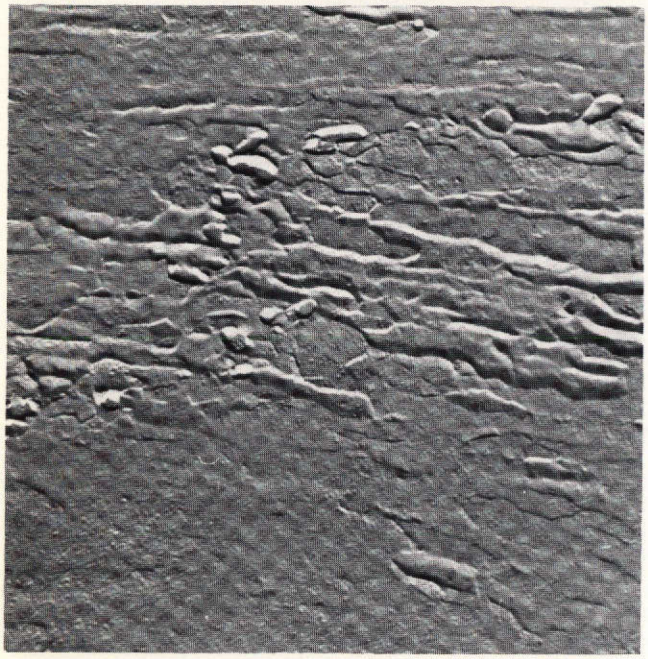


SPECIALLY PROCESSED TZM DISC FORGING (HEAT KDTZM-1175)
EDGE PERPENDICULAR TO RADIAL DIRECTION



TZM BAR (HEAT 7463)--LONGITUDINAL SECTION

FIGURE 2. MICROSTRUCTURES OF STRESS RELIEVED TZM. 100X



Heat KDTZM-1175 5000X

Heat KDTZM-1175 10,000X

Heat 7502 5000X

Heat 7502 10,000X

FIGURE 3. ELECTRON MICROGRAPHS OF PANCAKE FORGED AND STRESS RELIEVED TZM DISCS. TWO STAGE REPLICAS (CELLULOSE-NITRATE/CARBON) WITH CHROMIUM SHADOWING ON PRIMARY REPLICA. REDUCED 10% FOR REPRODUCTION.

Both the stress-relieved and recrystallized structures were studied in TZC. The two rolled plates had a uniform and relatively fine-grained microstructure in the stress-relieved condition, while the extruded and forged plate had a more irregular and somewhat coarser structure (Figure 4). The responses of the rolled plates to a 1 hour annealing treatment at 3092°F differed markedly; the plate from Heat M-91 which was given large reductions was fully recrystallized while the M-80 plate was only partially recrystallized (Figure 5). The difference presumably results from the higher degree of residual cold work in the plate finished at lower temperatures.

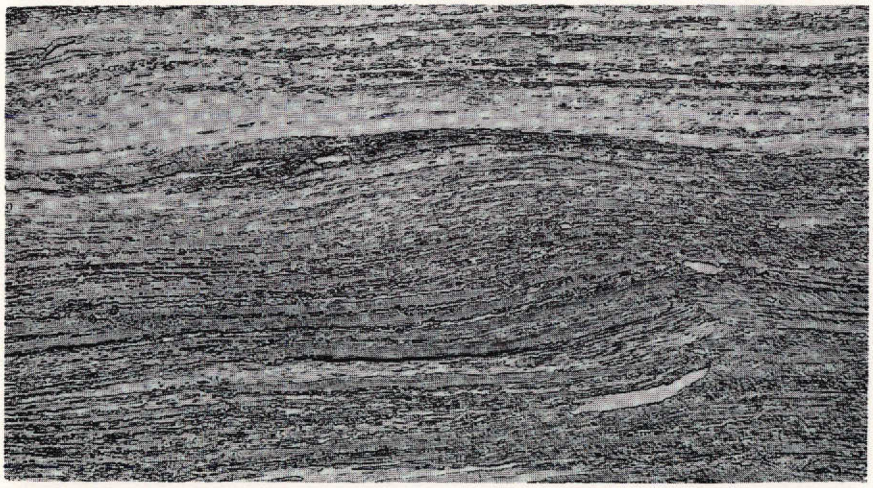
c. Tantalum Alloys

Pure tantalum was tested in the form of seamless tubing and plate. The tubing was produced by extrusion and drawing and was nominally 3/4 inch O.D. x 0.040 inch wall. One plate tested was rolled to 2-1/2 inch thickness, while the other plate was rolled to a nominal thickness of 0.160 inch. All of the tantalum materials were tested in the recrystallized condition, except where otherwise specified. Typical photomicrographs of the tantalum materials are shown in Figure 6.

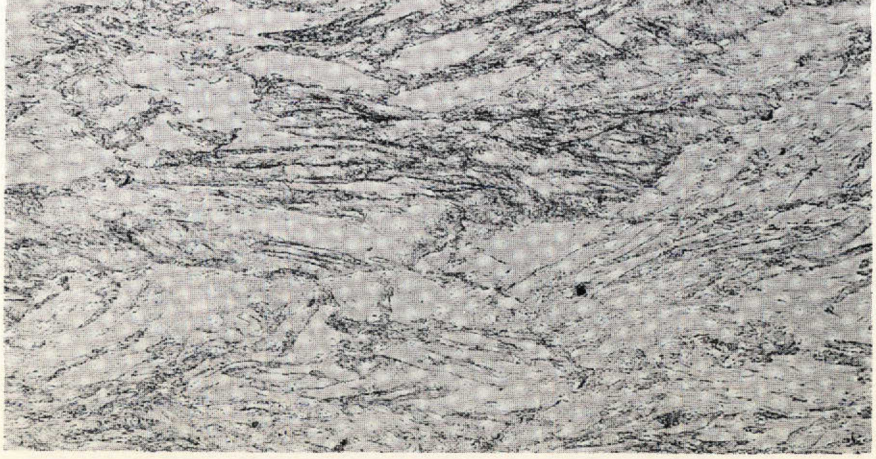
The Ta-10W alloy was tested in the form of nominal 0.030 inch sheet which was cold rolled and recrystallized 1 hour at 3000°F (1649°C). A photomicrograph of this material is shown in Figure 7.

Both T-111 and ASTAR 811C alloys were tested principally in the form of cold rolled and recrystallized nominal 0.030 inch sheet, except where noted otherwise. The standard annealing treatment for T-111 alloy was 1 hour at 3000°F (1649°C). Typical photomicrographs of T-111 in this condition are shown in Figure 8. The standard heat treatment for design tests on the ASTAR 811C alloy was 1/2 hour at 3600°F (1982°C). A photomicrograph of the ASTAR alloy in this condition is shown in Figure 9. Several other heat treatments were also used in an experimental program to determine the influence of annealing treatments on the creep strength of this material. These treatments involved temperatures in the range of 3000 to 3600°F (1649 to 1982°C) and times as long as 24 hours.

ROLLED PLATE--HEAVY DRAFTING PRACTICE, LOW TEMPERATURE FINISH (HEAT M-91)--LONGITUDINAL VIEW

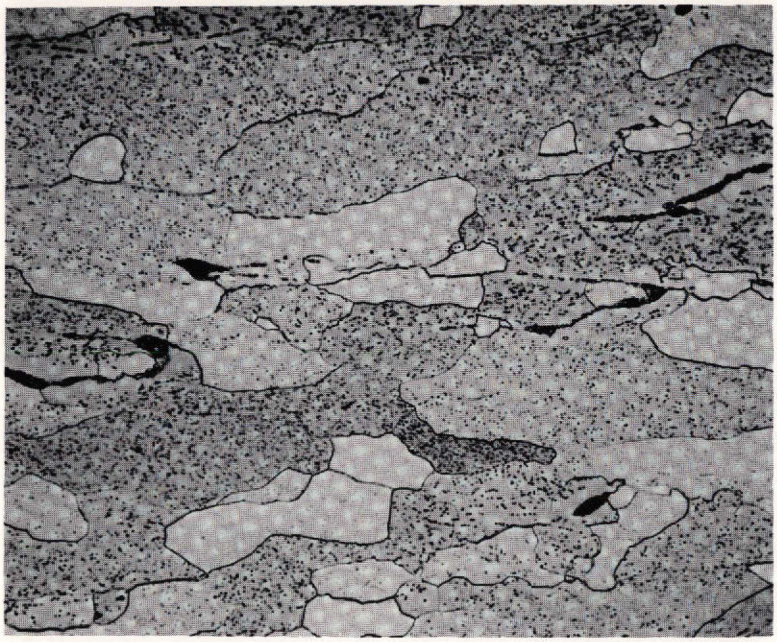


ROLLED PLATE--LIGHT DRAFTING PRACTICE, HIGH TEMPERATURE FINISH (HEAT M-80)--LONGITUDINAL VIEW

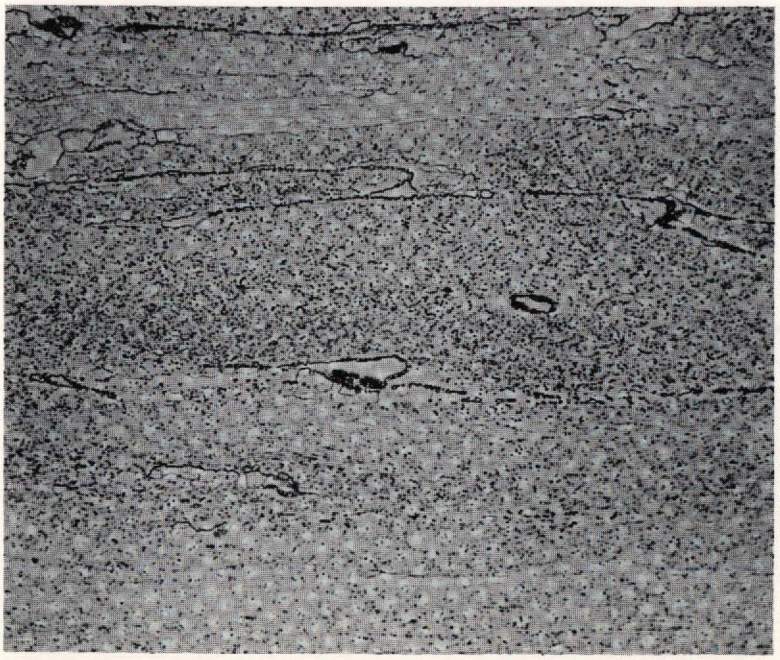


FORGED PLATE (HEAT 4345) EDGE OF PLATE PERPENDICULAR TO ORIGINAL EXTRUSION DIRECTION

FIGURE 4. MICROSTRUCTURES OF STRESS RELIEVED TZC. 100X

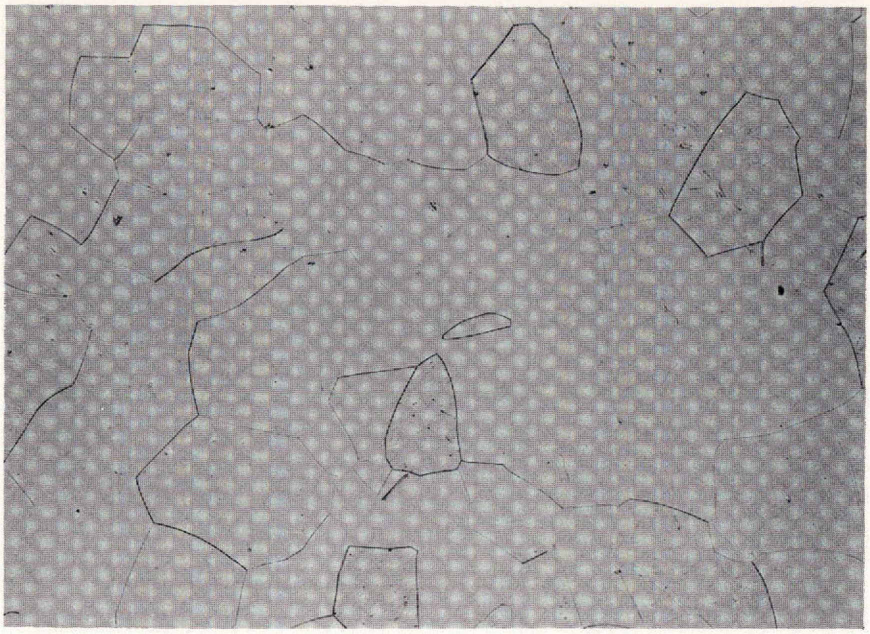


HEAVY DRAFTING PRACTICE, LOW TEMPERATURE FINISH
(HEAT M-91)

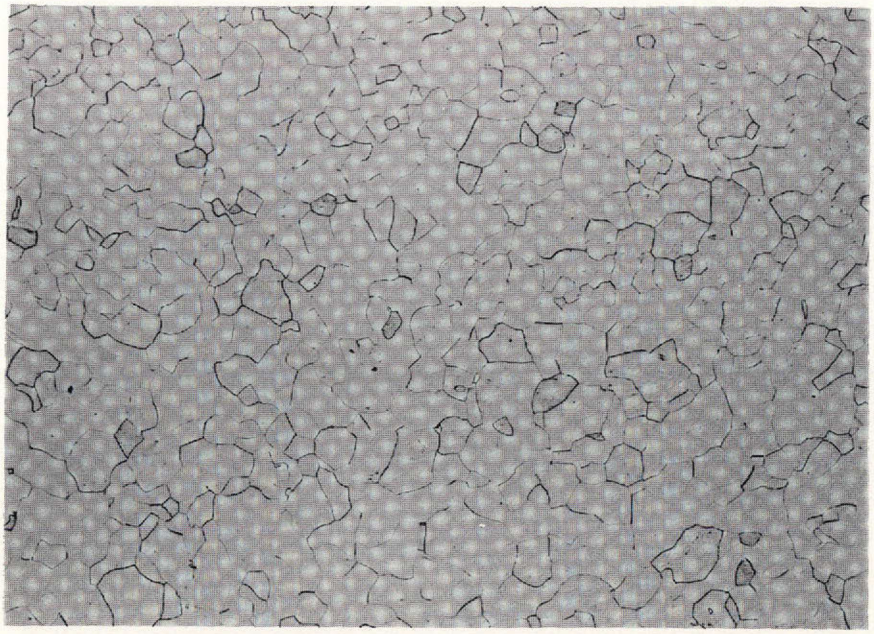


LIGHT DRAFTING PRACTICE, HIGH TEMPERATURE FINISH
(HEAT M-80)

FIGURE 5. LONGITUDINAL MICROSTRUCTURES OF TZC ROLLED PLATES AFTER ANNEALING 1 HOUR AT 3092°F. 500X



HEAT B-1962 ANNEALED 1 HOUR AT
1832°F (1000°C) 100X, HARDNESS 94KHN



HEAT 60249 ANNEALED 0.1 HOUR AT
2290°F (1254°C) 100X, HARDNESS 90KHN

FIGURE 6. MICROSTRUCTURES OF PURE TANTALUM TUBING.

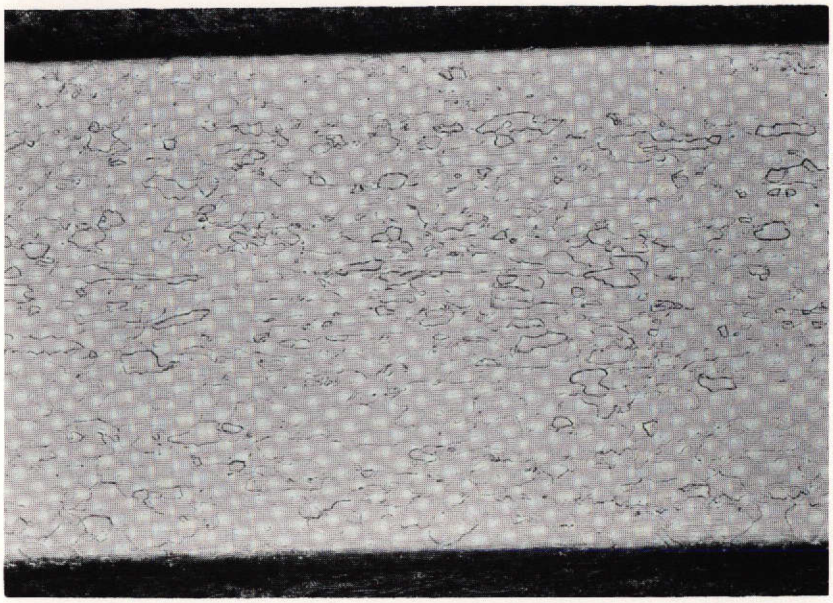
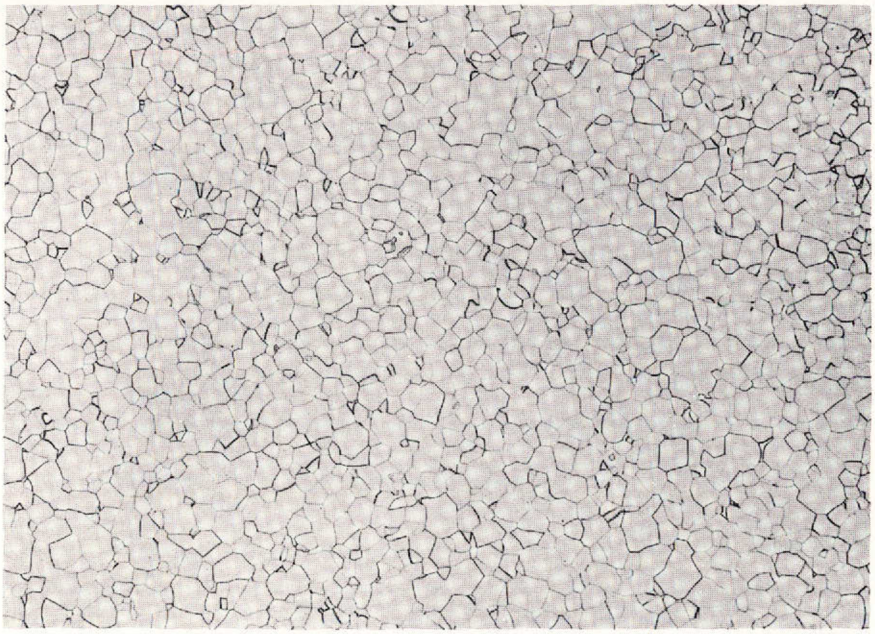
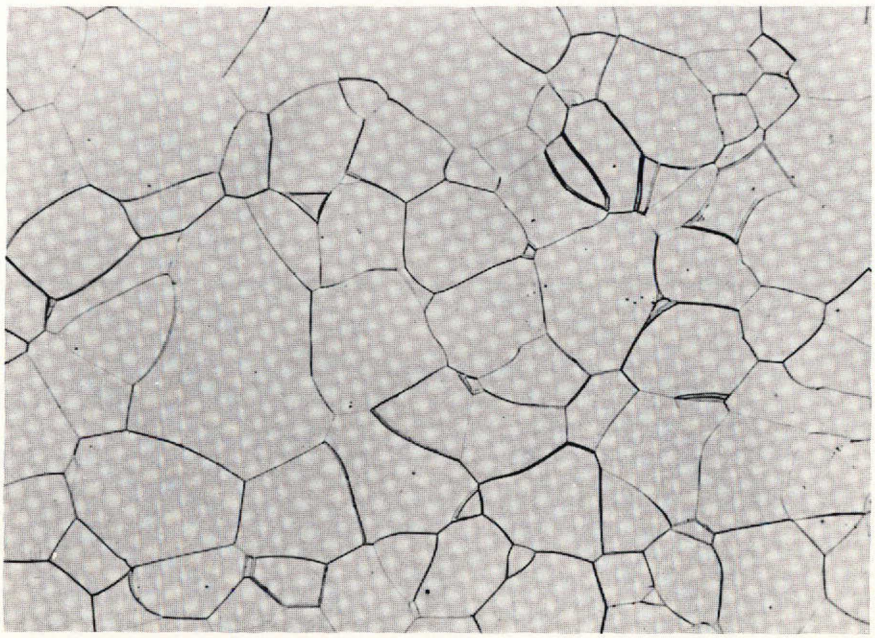


FIGURE 7. MICROSTRUCTURE OF Ta-10W ALLOY ANNEALED 1 HOUR AT 3000°F. 100X



100X



500X

FIGURE 8. OPTICAL PHOTOMICROGRAPHS OF T-111 HEAT NO. 70616 RECRYSTALLIZED 1 HOUR AT 3000°F (1649°C).

4039 B

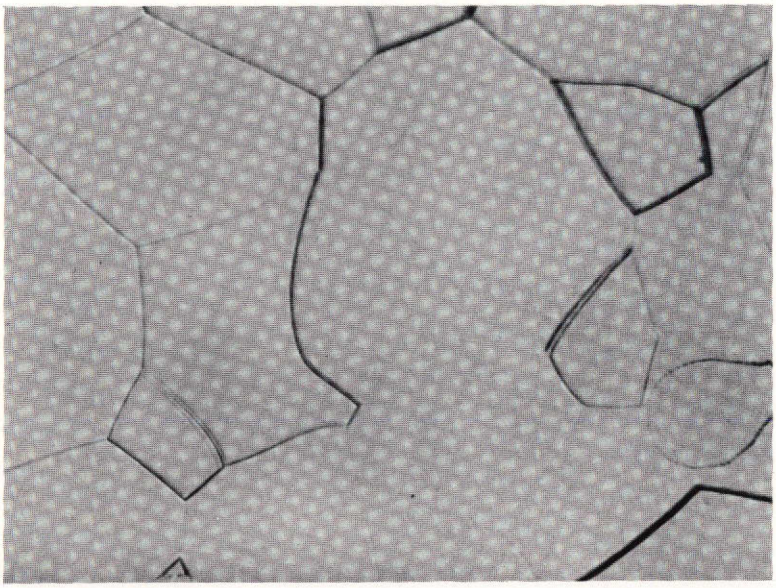


FIGURE 9. ASTAR 811C HEAT NASV-20-WS ANNEALED 30 MINUTES AT 3600°F.

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RESULTS AND DISCUSSION

A listing of the reports published under contracts NAS-3-2545 and NAS-3-9439 is included in Appendix I while a complete summary of all of the creep life data generated on the refractory alloy creep program appears in Appendix II. Creep curves representing all of the data generated under Contract NAS-3-9439 are presented in Appendix III. A detailed discussion of the significant findings for each test material is presented below.

1. Molybdenum Base Alloys

Creep tests were conducted on TZM and TZC to determine the influence of processing history and microstructure on the creep strength of these alloys.

The TZC alloy showed significant variability of creep strength with structure and heat treatment. The 1/2% creep life data on the Larson-Miller plot in Figure 10 indicate that in the annealed condition the rolled plate with the partially recrystallized structure (Heat M-80) had better creep resistance than the fully recrystallized plate (Heat M-91). The higher creep strength may be partially due to the more complex substructure associated with the higher yield strength of the cold worked material, or may result from the somewhat higher carbon level in Heat M-80. Analysis of the mechanical property data indicated that between the three TZC forms tested, Heat 4345 represented the best combination of creep strength and room temperature ductility.

The TZM test results, summarized in Figure 11 on a 1/2% creep Larson-Miller plot, show the superior creep strength of the specially processed disc forging. Although the electron microscopy of the TZM alloys (Figure 3) revealed a somewhat higher number of carbides in the specially forged material, neither forging possessed a carbide dispersion which appeared appropriate for dispersion strengthening. This indicated that the improved creep strength of Heat KDTZM-1175 may also be associated with the coarser grain structure shown in Figure 2, with the increased carbide density playing a complementary role by providing an improved thermal stability to the cold worked structure.

Comparison of the TZC and TZM results indicated that at higher stress levels and lower temperatures, the specially processed TZM was superior to TZC in the stress relieved condition, while at the lower stress levels the behavior of the two materials was comparable. The elevated temperature yield strength of TZM Heat 1175 was superior to TZC, (Table 3), and this factor was believed to be associated with the improved creep strength in the higher stress range.

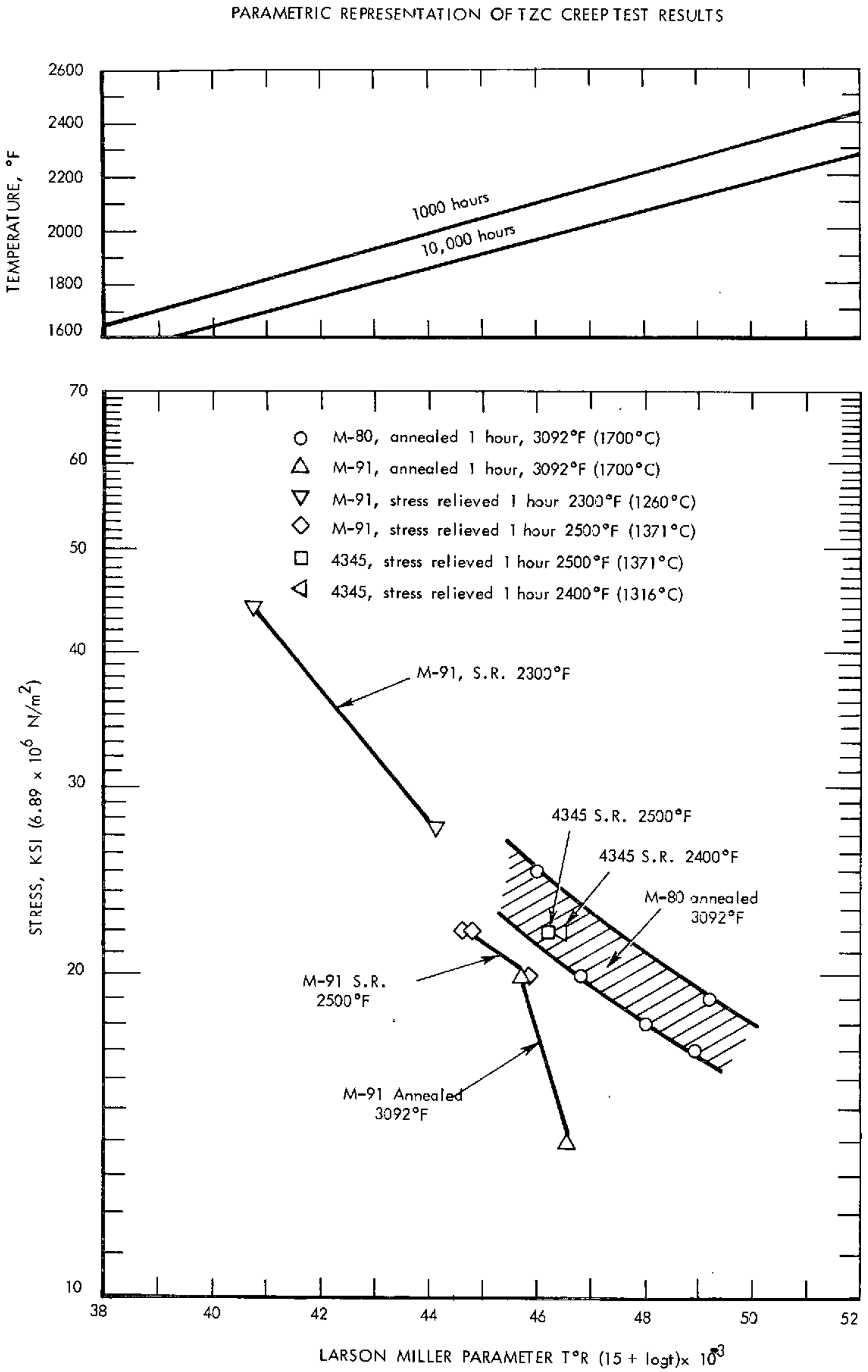

FIGURE 10. PARAMETRIC REPRESENTATION OF TZC 0.5% CREEP TEST RESULTS.

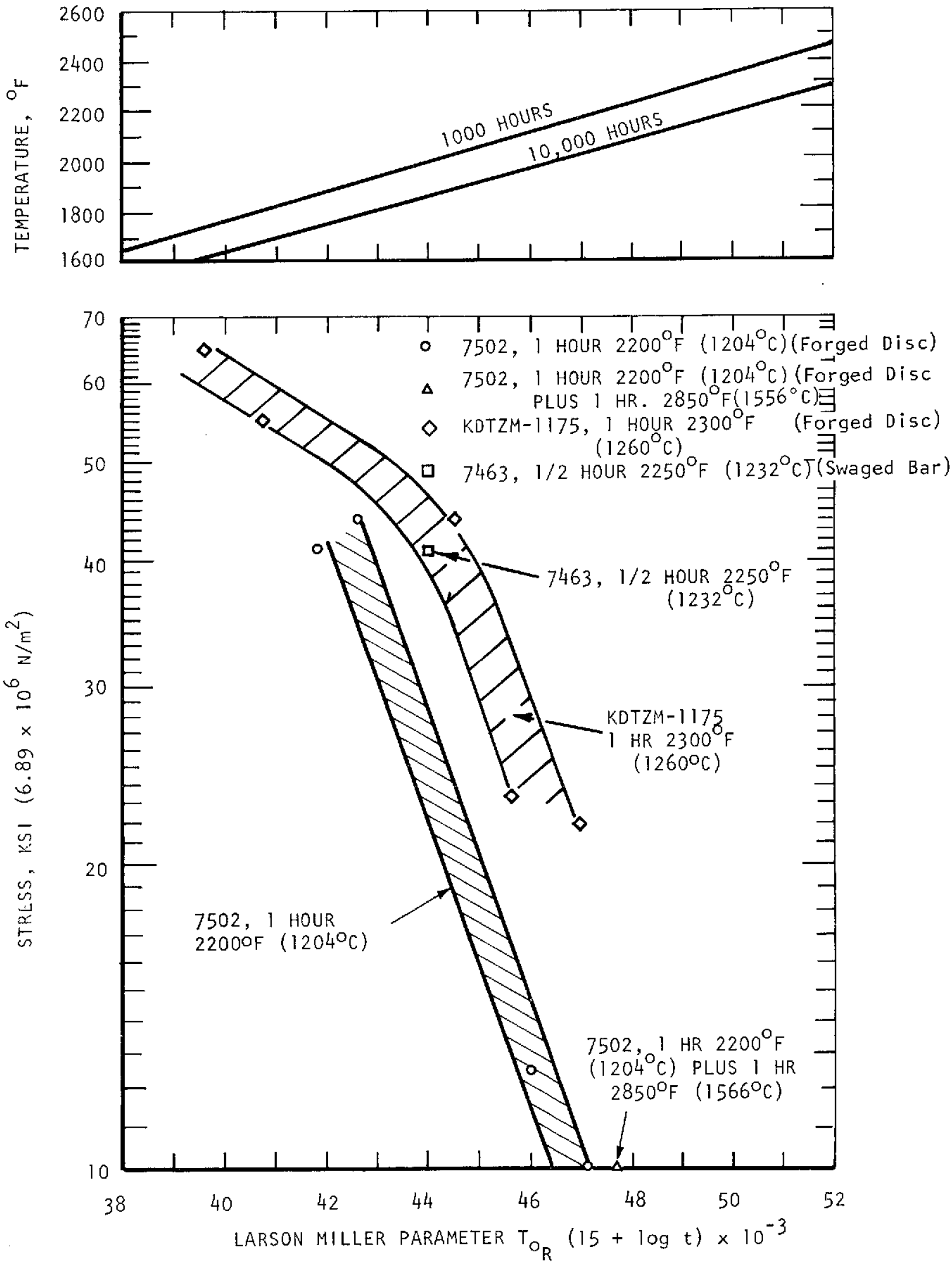

FIGURE 11. 1/2% CREEP TEST RESULTS FOR TZM TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR.

TABLE 3

TENSILE PROPERTIES OF STRESS RELIEVED TZC AND TZM AT 2000°F

Material	Stress Relief Temperature °F	Ultimate Strength ksi	0.2% Offset Yield Strength, ksi	Percent Elongation	Percent Reduction of Area
TZM Heat KDTZM-1175	2300	79	74	19	51
TZC Heat 4345	2500	70	69	18	61

None of the molybdenum base alloys tested showed a significant change of structure or composition as a result of the long time elevated temperature exposure to ultrahigh vacuum, although a modest increase of strength resulted from the relatively small creep strains achieved.

2. Tantalum Base Alloys

One percent creep life results for pure tantalum and the tantalum base alloys T-111, Ta-10W and ASTAR 811C are presented on a Larson-Miller plot in Figure 12, together with data from the literature on ASTAR 811C (5). A discussion of these results follows.

a. Pure Tantalum

The primary application toward which the pure tantalum testing was directed is a SNAP 8 tube-in-tube Hg-NaK heat exchanger assembly described recently by Gertsma and Medwid (6). Most of the effort was concentrated on the pure tantalum tubing which forms the inner element of the boiler, although near the end of the program significant attention was directed toward the dome-shaped manifolds which distribute and collect fluid flow at each end of the boiler. Three basic material conditions were tested; recrystallized, recrystallized and welded, and recrystallized and pre-strained. Results from the recrystallized tests of the tubing and plate (Figure 12) tend to fall into two separate ranges, depending on the grain size of the test material. The larger-grained specimens tended to be weaker than the smaller-grained samples, which is typical of material creep tested below the so-called "equi-cohesive" temperature where grain boundary sliding becomes an important deformation mechanism.

The results in Figure 12 also indicate that creep resistance of a tube containing transverse bead-on-plate TIG weld was comparable to the unwelded tubing, despite the appearance of significantly accelerated creep adjacent to the weld bead (see Figure 13). Visual examination of this area

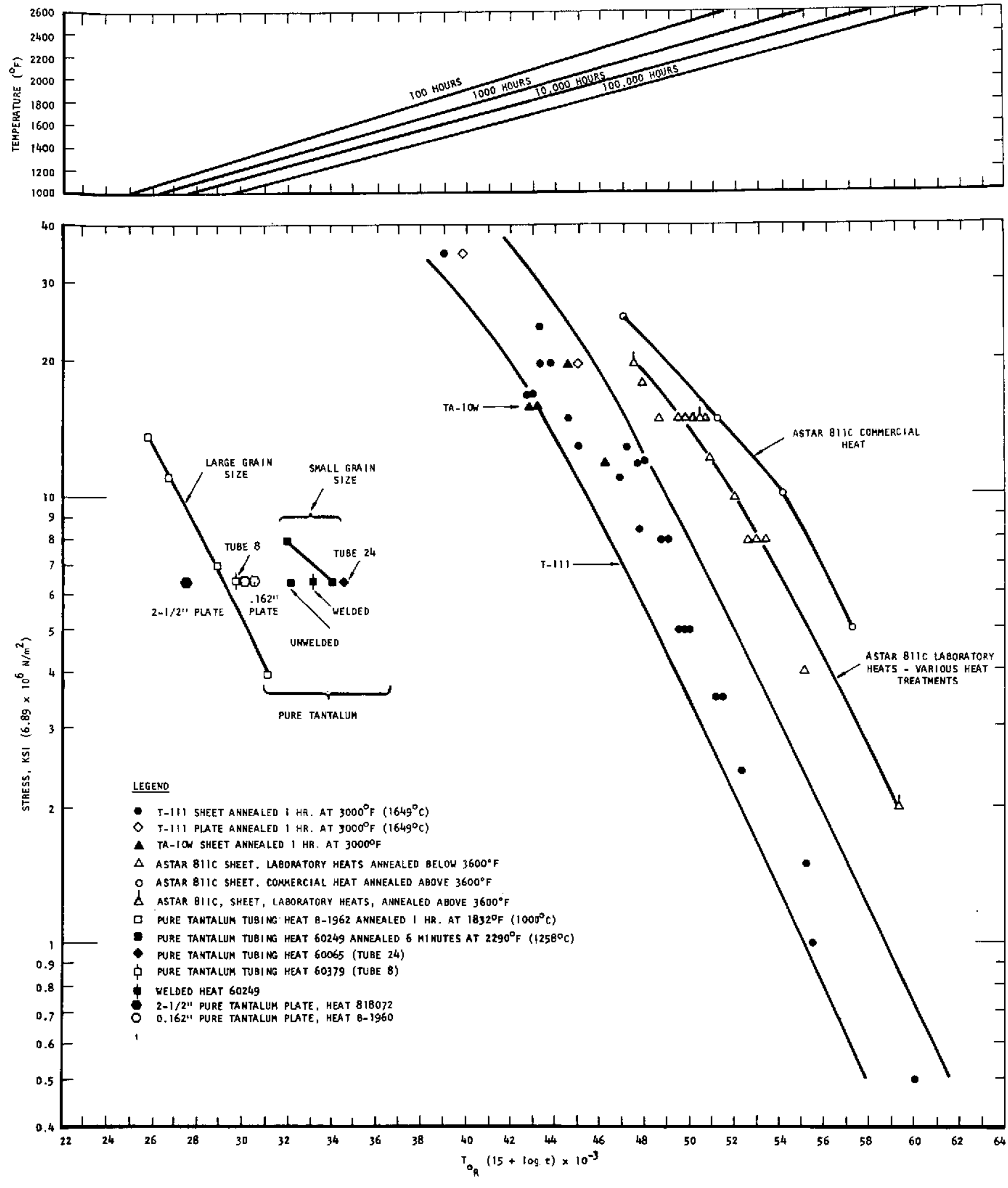

FIGURE 12. LARSON-MILLER PLOT OF 1 PERCENT CREEP LIFE DATA FOR TANTALUM-BASE ALLOYS CREEP TESTED IN A VACUUM OF <1 x 10^{-8} TORR.

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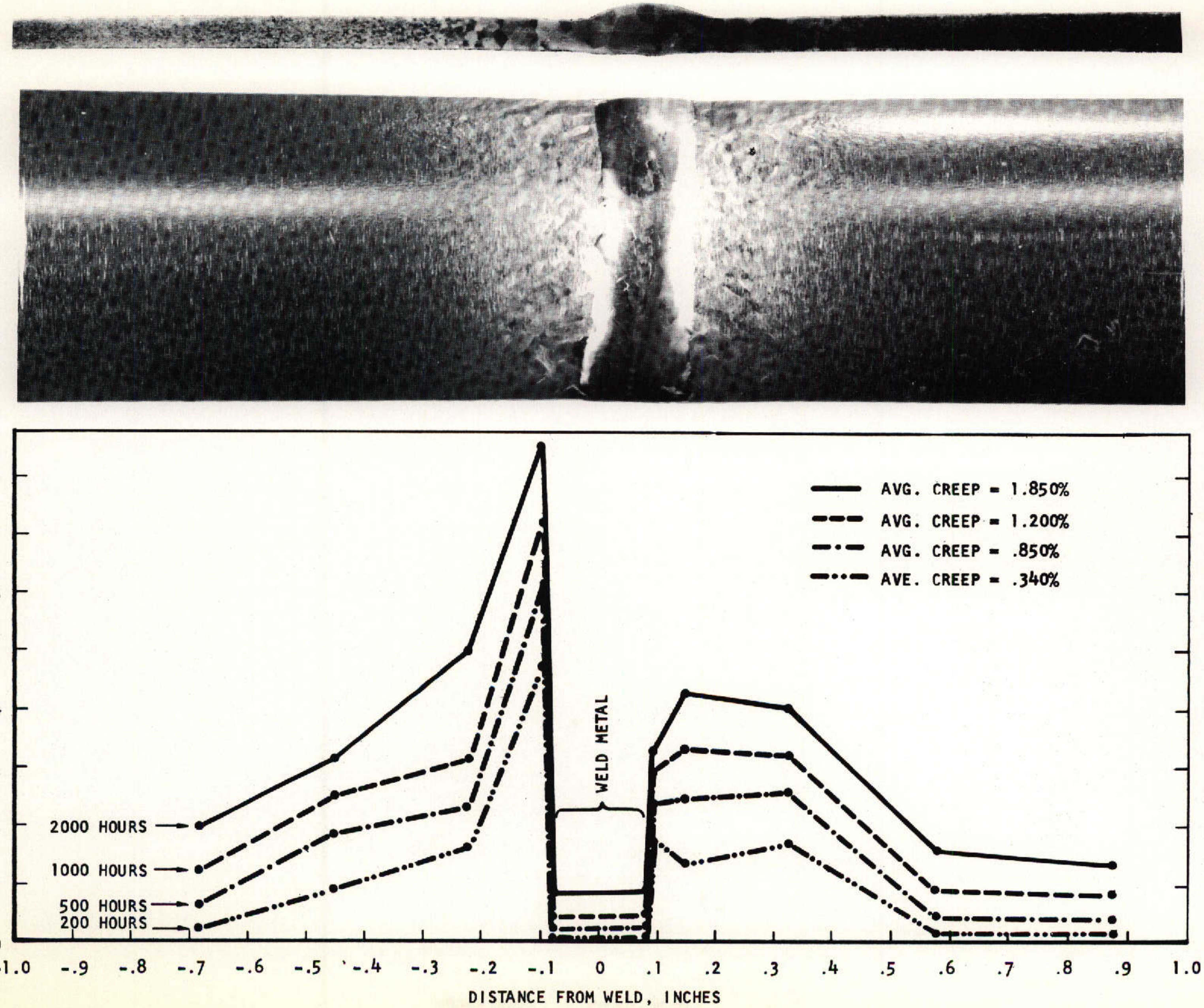


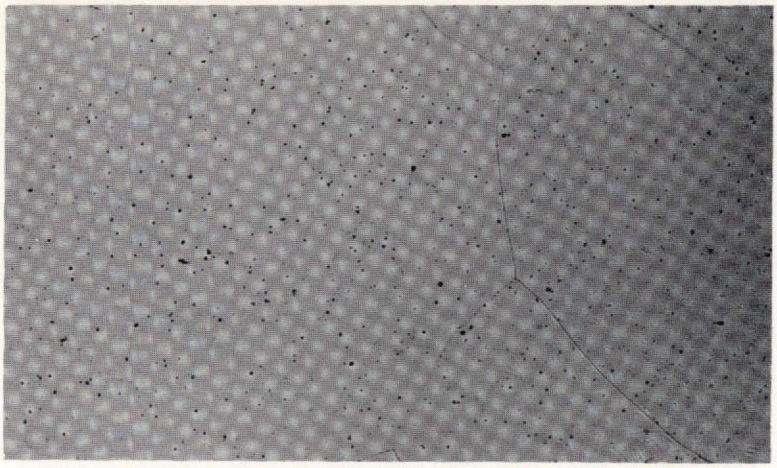
FIGURE 13. CREEP BEHAVIOR OF WELDED PURE TANTALUM TUBING.

revealed a heavy orange peal effect in what is presumably the heat affected zone, indicating that the accelerated creep resulted from grain growth in this region. Examination of the cross-section shown in Figure 13, together with photomicrographs of the weld bead, the heat affected zone and the base metal (Figure 14), confirmed this hypothesis.

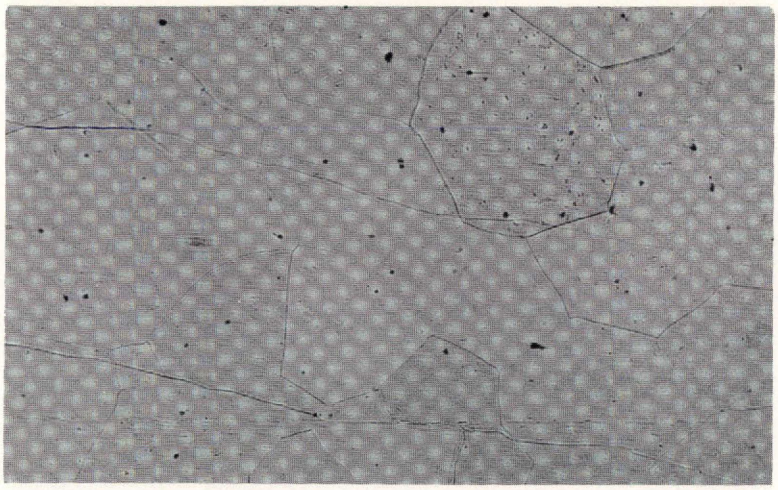
Two reasons may be advanced to account for the fact that the overall creep behavior of the welded tube was comparable to the unwelded tubing despite the appearance of accelerated creep in the heat affected zone. First, essentially no creep occurred in the weld bead, which is considerably thicker than the base tube wall. This reduces somewhat the overall specimen extension compared with an unwelded tube. Second, while the creep rate is significantly higher in the heat affected zone, the length of this zone is small enough so that the cumulative extension is not large compared to the total extension over the full 2-inch gauge length. However, in spite of this apparently high weld efficiency, a potential problem exists for longer test times in the form of a slight neck which can be seen developing on the left side of the weld bead in Figure 13. Because of this necking it would appear that the effect of welding on creep could still cause difficulty in a welded assembly.

Additional tests on pure tantalum were directed toward characterization of the creep behavior of the manifolds which distribute and collect fluid flow at each end of the boiler. A section of one of these manifolds is shown in Figure 15. Because this part was formed by cold drawing, some concern exists regarding the relevance of recrystallized creep data to the operating component. Since direct creep testing of the header itself would be quite difficult, the approach was to calculate the total cold strain in the important areas of the manifold and to duplicate this strain as closely as possible using uniaxial tensile deformation prior to creep testing. The maximum effective strain in the manifold was estimated by measuring the dimensions and comparing them with the dimensions of the die and the blank from which the part was formed. Results of this analysis indicated effective strains on the order of 35 to 45% in the critical areas of the manifold.

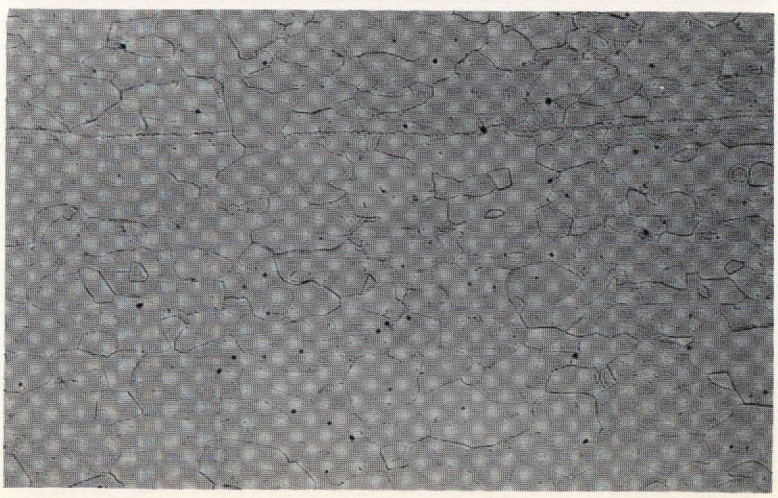
On the basis of this analysis, an effort was made to tensile prestrain a pure tantalum creep specimen 40% prior to testing. Unfortunately, it was found that the maximum uniform elongation which could be achieved in this manner was 30%. However, since the entire approach was considered to be only a first order approximation, it was decided to creep test the 30% pre-strained specimen with the thought that this structure was a better approximation to the cold-drawn manifold than the annealed plate. Results of this test (Table 4) show a drastic difference between the creep behaviors of the annealed and the prestrained material, indicating the need for an expanded effort to characterize the exact structure in critical stress areas of the cold formed manifold and to creep test material having that structure.



(a) WELD BEAD



(b) HEAT AFFECTED ZONE



(c) BASE METAL

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FIGURE 14. MICROSTRUCTURES OF WELDED PURE TANTALUM CREEP SPECIMEN. 100X

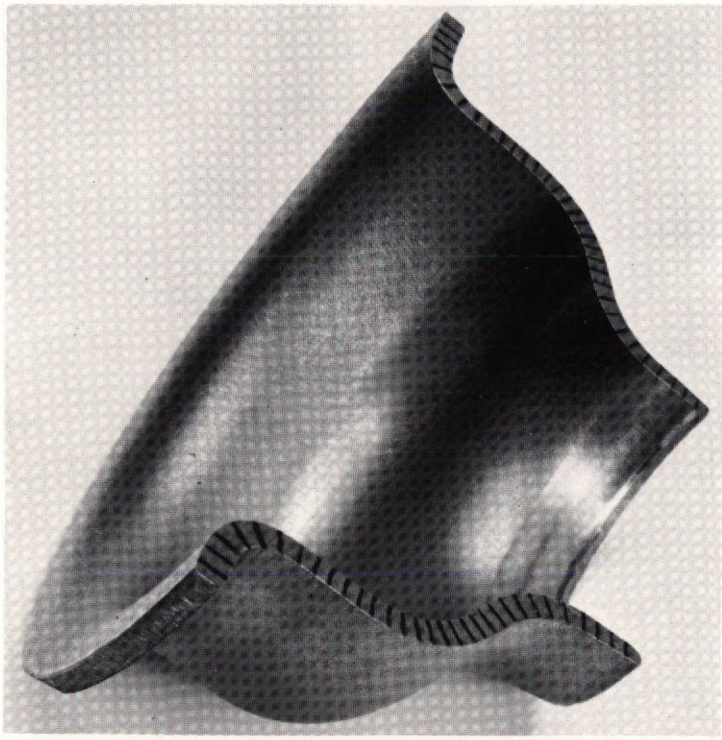

FIGURE 15. PHOTOGRAPH OF PURE TANTALUM MANIFOLD.

Table 4

Creep Life Data, Pure Tantalum Heat No. B-1960, Recrystallized (Heat Treatment Conditions Unknown) and Pre-Strained 30% in Tension Prior to Creep Testing. Creep Test Conditions 1350°F (732°C), 6.5 ksi (44.8 MN/m^2)

One Percent Creep Life, Hours	
Recrystallized	Pre-Strained
45*	37,000**

* Average of two tests
** Extrapolated

b. ASTAR 811C Alloy

The effect of annealing time and temperature on grain size, precipitate morphology, tensile properties and creep strength was determined for the high strength tantalum-base alloy ASTAR 811C. Creep life data for ASTAR 811C alloy are separated into two distinct groups in Figure 12. One includes data for the two laboratory heats tested while the other represents a commercial heat of this material. The commercial heat was significantly stronger than the laboratory material when annealed 1/2 hour at 3600°F (1982°C).

In addition to this dependence of creep strength on material source, the creep strength of the laboratory heats was found to vary significantly with the heat treatment. Preliminary work at the Westinghouse Astronuclear Laboratories (7), where this alloy was developed, indicated that the creep strength of the ASTAR alloy could be improved by annealing at or above 3600°F (1982°C). In an effort to clarify the reasons for this behavior, a study was conducted to determine the influence of heat treatment on the grain size and precipitate morphology in ASTAR 811C. Figure 16 is a plot of grain size versus a Larson-Miller parameter calculated from the heat treatment time and temperature. The constant of 8 was chosen by successive approximation to give the best correlation of the data. The results presented on this plot include both the data generated in this program and results obtained by Westinghouse (7). Results of the study of precipitate morphology are shown in Figure 17. These electron micrographs indicated that the carbide solvus temperature for this composition lies between 3520 and 3560°F (1940 and 1961°C). It is interesting to note that the room temperature yield strength of this material also increased abruptly by about 10% in this same temperature range (Table 5).

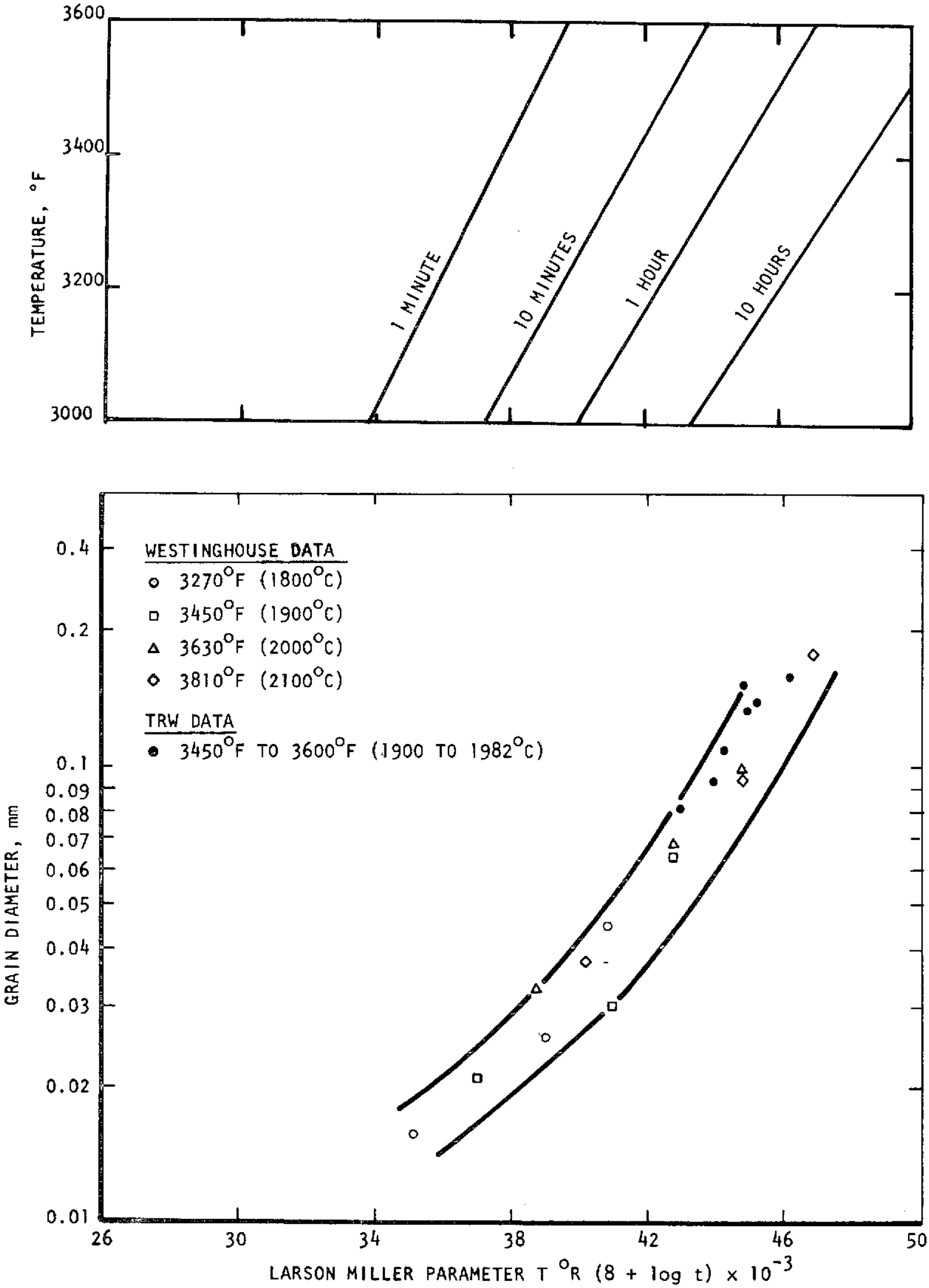

FIGURE 16. LARSON-MILLER PLOT OF GRAIN GROWTH DATA FOR ASTAR 811C COLD ROLLED TO 85% R.A.

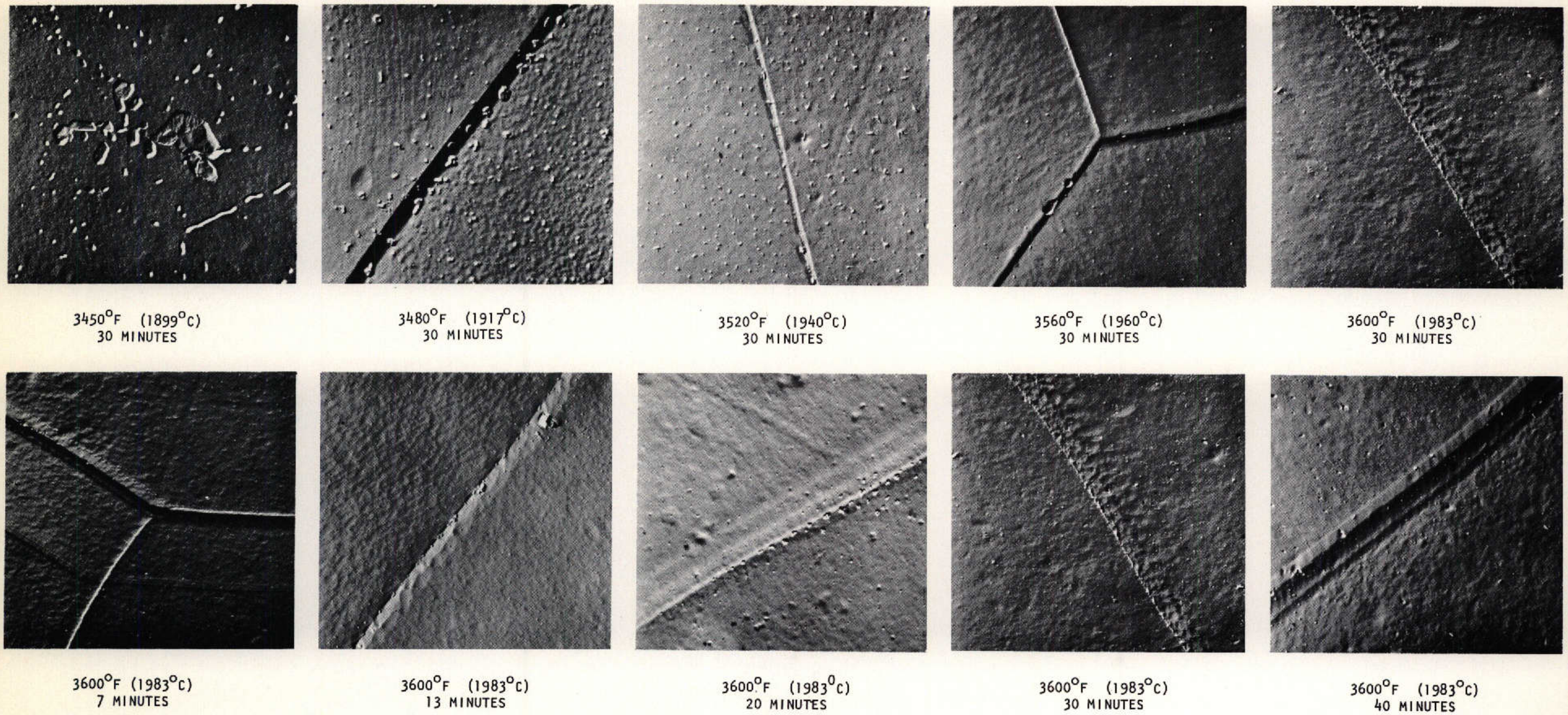

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FIGURE 17. INFLUENCE OF ANNEALING TIME AND TEMPERATURE ON THE PRECIPITATE MORPHOLOGY IN TANTALUM-BASE ASTAR 811C, HEAT NO. NASV-20-WS

Table 5

Influence of Annealing Time and Temperature on the Grain Size and Room Temperature Mechanical Properties of ASTAR 811C

Heat No.	Annealing Time, Min.	Annealing Temp. °F	°C	Grain Size mm	Ultimate Tensile Strength KSI	0.2% Yield Strength KSI	Percent Elongation
*VAM-95	60	3000	1649	0.01	110.8	87.0	24
*NASV-20-WS	60	3000	1649	0.02	105.4	83.4	24.8
*NASV-20-WS	60	3272	1800	0.05	104.6	84.3	23.1
VAM-95	20	3480	1915	0.054	96.7	81.2	27.7
VAM-95	15	3520	1938	0.066	96.4	84.3	28.2
VAM-95	12	3560	1960	0.066	101.7	92.1	29.2
VAM-95	9	3600	1982	0.068	101.0	92.4	25.9
*NASV-20-WS	60	3633	2000	0.180	105.3	90.0	23.2
*NASV-20-WS	60	3633	2000 plus Helium Quench	0.180	108.8	102.7	17.0
*NASV-20-WS	60	3993	2200	0.400	105.0	103.2	18.4

* Westinghouse Data (8)

At first glance it would appear that the improved creep strength of the hot annealed material is caused by a solutioning of the carbides during heat treatment, followed by reprecipitation in a more favorable morphology during cooling. However, since grain size is known to have a significant influence on creep behavior, it was felt that this factor could not be overlooked as another possible source of the improved strength. In order to clarify this point two tests were conducted on specimens annealed at temperatures below the carbide solvus temperatures for times long enough to develop a grain size equivalent to that produced at the higher annealing temperature. Results of these tests, shown in Table 6, demonstrate that the improved creep strength can indeed be developed at the lower annealing temperatures by increased grain size if the annealing times are long enough.

Table 6

Influence of Heat Treatment on the Grain Size and 1% Creep Life of ASTAR 811C Heat VAM-95 Creep Tested at 2400°F (1316°C) and 15 ksi (103 MN/m²)

Test No.	Time	Temperatures °F	°C	1% Creep Life Hours	Grain Size MN
S-73	1/3	3600	1982	435	.09
S-79	5	3450	1800	542	.12
S-81	24	3270	1700	560	.12*
S-75	1	3000	1649	144	.01*

* Estimated

Another important observation associated with this problem concerns the variation of carbide morphology during creep testing. Electron microscopy performed on specimens annealed above the carbide solvus temperature and creep tested in the 2000 to 2400°F (1093 to 1316°C) range showed coarse carbides located principally in the grain boundaries after testing. However, no significant creep rate transition occurred during such tests, despite this significant change of carbide morphology. This result, together with the fact that the improved creep strength could be developed by annealing below the carbide solvus temperature, indicated that grain size is an important factor in determining the creep behavior of ASTAR 811C.

c. T-111 Alloy

In an effort to gain a better understanding of the creep behavior of T-111 alloy, an analysis was made to relate the creep behavior with strain aging effects known to exist in these alloys (1). The design data are reproduced in Figure 12, and the pertinent conclusions are summarized below. Analysis of T-111 tension test data revealed a strong strain aging phenomenon in the temperature range of 1100 to 2100°F (593 to 1149°C), which was thought to result from a complex atmosphere-dislocation interaction. Activation energy measurements showed that oxygen was the interstitial atom species involved in this interaction. Comparison of these results with the T-111 creep data indicated that the strain aging reaction was associated with an unusual transient creep behavior observed in the same temperature range. This transient strengthening, which is illustrated schematically in Figure 18, caused the creep rate to drop to essentially zero at very low strain levels (0.1%), even at stresses approaching the yield strength. However, this transient strengthening gradually lost its effectiveness at higher strain levels. Pre- and post-test chemical analyses indicated that this creep rate transition is caused by a loss of oxygen, which is the interstitial atom species responsible for the strain age strengthening. Analytical treatments of the creep data showed that the steady state creep rates which were established after the creep rate transition could be correlated with normal steady state creep rates measured at temperatures above the strain aging temperature range using the single phenomenological equation:

$$\dot{\varepsilon} = 1.65 \times 10^{9} \left[\sinh(6.6 \times 10^{-5}\sigma)\right]^{3.17} e^{\frac{-90,000}{RT}}$$

where $\dot{\varepsilon}$ is the steady state creep rate, σ is stress in psi, T is temperature in °K, and R is the universal gas constant (1.987 cal./mole K°).

d. Creep Behavior Under Variable Temperature and Stress Conditions

The behavior of tantalum-base alloys under conditions of variable stress and temperature becomes a critical consideration because the proposed application of refractory alloys as structural materials in radioisotope capsules. This application provides an unusual design problem in that some of the isotopes under consideration produce gaseous decay products. The capsules are fabricated under high vacuum; and since safety considerations preclude venting, the capsule interior is subjected to continuously increasing gas pressure after the shell is sealed. In addition, the temperature of the capsule gradually drops from its initial value because of radioactive decay. As a result, the structural liner is simultaneously subjected to increasing stress and decreasing temperature. In order to characterize material behavior under these design conditions a program was conducted to determine the creep behavior of T-111 alloy under the influence of continuously increasing stress. Results of this program have been previously described (2) and are summarized below.

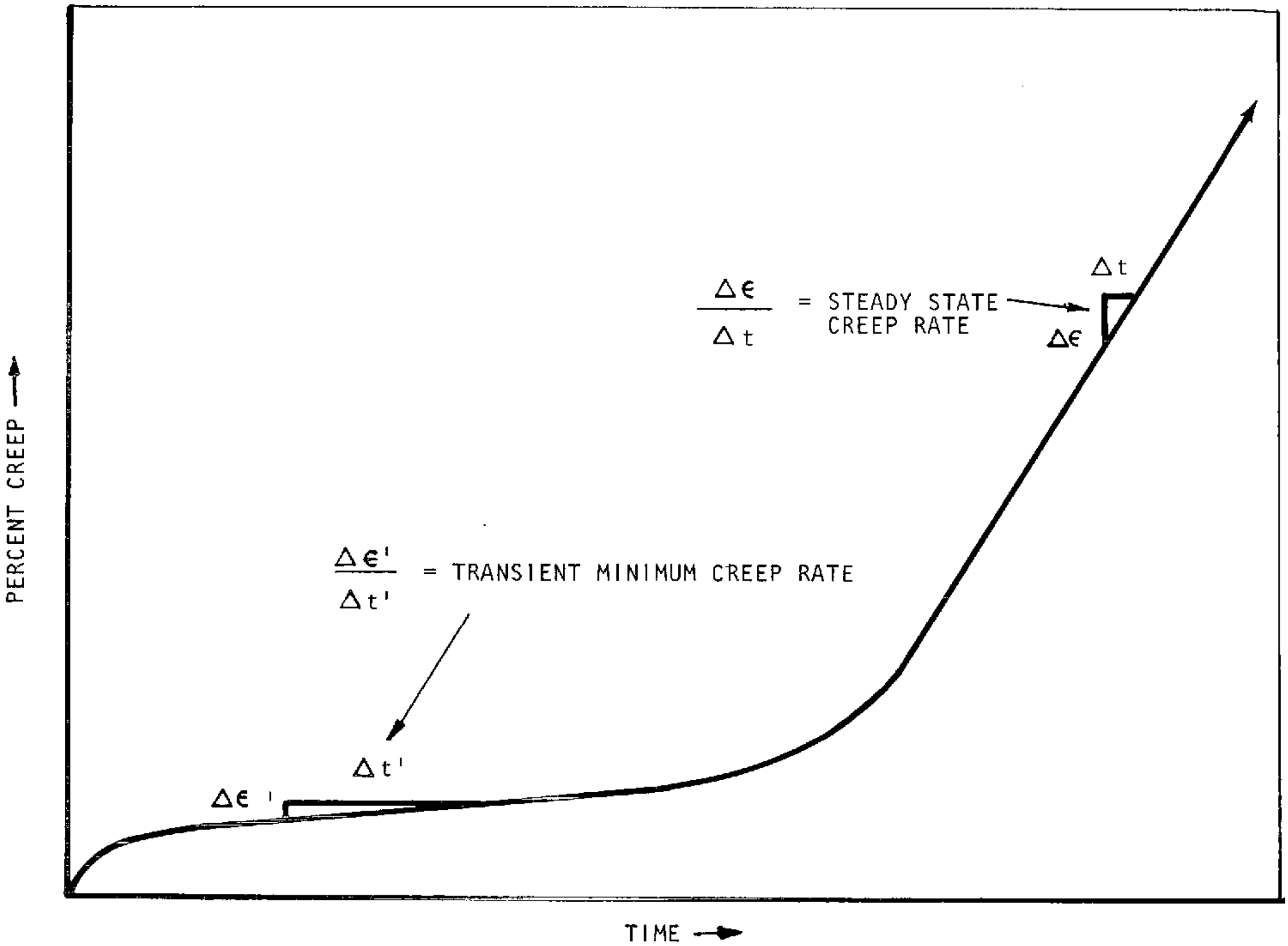

FIGURE 18. SCHEMATIC REPRESENTATION OF T-111 CREEP BEHAVIOR IN THE 1200 TO 2000°F (649 TO 1204°C) RANGE, SHOWING THE UNUSUAL NATURE OF THE TRANSIENT FIRST STAGE CREEP IN THIS ALLOY.

The ultrahigh vacuum creep tests made on tantalum-base T-111 alloy with continuously increasing loads showed that the creep rate increased steadily with test time and that the instantaneous creep rates measured in this type of test were comparable to isostatic steady state creep rates at equivalent stress levels. Reasons for this identity of strain rates were discussed in terms of the ultrahigh vacuum deoxidation which occurs during creep testing of T-111. A technique was developed to correlate the variable stress 1% creep life with temperature and stress rate on a parametric basis, and methods for prediction of the increasing stress 1% creep life from isostatic test data were developed and compared with the experimental data.

Another experimental program is in progress to study the creep behavior of T-111 with continuously decreasing temperature. While there are not enough data available from this program for a complete analysis, preliminary results indicate creep behavior of T-111 under these test conditions can be predicted from isothermal creep results using the same analytical techniques which were developed for the variable stress data (2).

A third series of tests is planned in which both stress and temperature will be varied simultaneously. Each of these test programs is being correlated with analytical studies of the relationship between isostatic-isothermal and variable-stress, variable-temperature creep behavior.

e. Ta-10W Alloy

A limited number of creep tests were conducted on recrystallized Ta-10W alloy to determine the relative creep resistance of this material with respect to the other tantalum alloys. Comparison of the results of these tests (Figure 12) with the T-111 data indicate that the creep strengths of these two alloys were comparable over the 12 to 20 ksi (82.7 to 138 MN/m^2) stress range examined.

3. W-25%Re Alloy

A small test program was undertaken to study the suitability of stress relieved W-25%Re for the fabrication of bellows in high vacuum instrumentation applications. The purpose of this program was to determine the minimum temperature and stress which would produce a measurable time dependent plastic strain. A sequential evaluation was made which involved five successive 200-hour tests at 50°F intervals between 1600 and 1800°F (870 to 982°C) at a stress of 15 ksi (104 MN/m^2). (A preliminary test series showed that no creep occurred in this temperature range at 10 ksi (68.9 MN/m^2).) Results of the 15 ksi series indicated very little creep

(<1.25 x 10^{-7} in/in/hour) at 1600 and 1650°F (869 and 900°C), but measurable creep did occur at the three highest test temperatures, as shown in Table 7. The figures presented in this table represent only the true plastic extension which occurred during each sequence, and do not include the thermal expansion between sequences, which accounted for the majority of the observed deformation. The results indicated that at the 15 ksi (104 MN/m^2) stress involved in the bellows applications a relatively low creep rate would occur at temperatures to 1800°F (980°C).

Table 7

W-25%Re 15 ksi (104 MN/m^2) Sequential Test Results

Temperature °F	°C	Percent Creep in 200 Hours at Test Temp.	Creep Rate, in/in/hr
1600	869	Negligible	<1.25 x 10^{-7}
1650	900	Negligible	<1.25 x 10^{-7}
1700	927	.0085	4.2 x 10^{-7}
1750	954	.0115	5.8 x 10^{-7}
1800	980	.0140	7.0 x 10^{-7}

CONCLUSIONS

1. Results of sequential tests on W-25%Re alloy showed that this alloy does not creep in the 1600 to 1800°F (870 to 982°C) range at 10 ksi (6.89×10^7 N/m^2), nor in the 1600 or 1650°F (870 or 900°C) range at 15 ksi (10.4×10^7 N/m^2). Significant creep has been detected in the 1700 to 1800°F (927 to 982°C) range at 15 ksi ($10x4 \times 10^7$ N/m^2).

2. Comparisons of TZC and TZM test results using the Larson-Miller parameter showed that composition and thermal-mechanical processing history significantly influence the 1/2% creep life. At higher temperatures and lower stresses the creep resistance of TZC and TZM are comparable in the stress relieved condition. However, in the low temperature and high stress range, a special heat of TZM processed at higher than normal temperatures and having a higher than normal carbon content shows the best creep resistance.

3. On the basis of a small number of selected tests the creep strength of Ta-10W alloy was comparable to that of T-111 alloy.

4. The creep strength of pure recrystallized tantalum below 1350°F (932°C) was dependent on grain size, with larger grain sizes providing poorer creep strengths.

5. Creep of pure tantalum in the heat affected zone of a bead-on-plate weld proceeded at a faster rate than in the base metal.

6. Results from a creep specimen of pure tantalum which was pre-strained 30% in tension prior to testing indicated that prior working significantly improved the creep strength of this material.

7. The creep strength of commercially produced ASTAR 811C was significantly higher than laboratory heats of this material.

8. Studies of the relationships between heat treatment, grain size, carbide morphology and creep strength have shown that the strengthening mechanism in ASTAR 811C is not due solely to carbide precipitation. The true nature of the creep strengthening in this alloy is not fully understood at the present time.

9. Analysis of T-111 alloy creep and tension test data indicated that complex atmosphere strain aging involving oxygen and probably hafnium provided a transient strengthening in the early stages of T-111 creep tests in the 1600 to 2200°F (870 to 1204°C) range. At long test times, ultrahigh vacuum removal of oxygen depleted the strain aging strengthening species from the matrix and caused a creep rate transition to occur.

After the creep rate transition, steady state creep proceeded according to the relationship:

$$\dot{\varepsilon} = 1.65 \times 10^{9} [\sinh(6.6 \times 10^{-5}\sigma)]^{3.17} e^{-90,000/RT}$$

where the values of activation energy and stress exponent suggested that steady state creep was governed by a diffusion controlled microcreep mechanism.

10. Ultrahigh vacuum creep tests made on tantalum-base T-111 alloy with continuously increasing loads showed that the creep rate increased steadily with test time, and that the instantaneous creep rates measured in this type of test were comparable to isostatic steady state creep rates at equivalent stress levels. Reasons for this identity of strain rates were discussed in terms of the ultrahigh vacuum deoxidation which occurred during creep testing. A technique was developed to correlate the variable stress 1% creep life with temperature and stress rate on a parametric basis and methods for prediction of the increasing stress 1% creep life from isostatic test data were also developed and compared with the experimental data.

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APPENDIX I

PREVIOUSLY PUBLISHED REPORTS

ON THE REFRACTORY ALLOY CREEP PROGRAM

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APPENDIX II

SUMMARY OF ULTRAHIGH VACUUM CREEP TEST RESULTS GENERATED ON THE REFRACTORY ALLOY CREEP PROGRAM

TABLE II-1. Summary of Arc-Melted Tungsten Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter T (15+logt)x10⁻³
S-5	KC-1357	24	3200	1760	3.0	20.7	3200	1760	6	32	5.38	57.8
S-7	KC-1357	2	3200	1760	0.4	2.8	3200	1760	***	714	118	***
S-9	KC-1357	2	3200	1760	1.0	6.9	3200	1760	675	3886	2.760	65.4
S-17	KC-1357	2	2800	1538	4.0	28.0	2800	1538	20	908	5.452	53.1
S-18	KC-1357	2	2800	1538	3.0	20.7	2800	1538	125	908	5.535	55.8

***Insufficient creep to extrapolate

TABLE II-2. Summary of Vapor-Deposited Tungsten Ultra-High Vacuum Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter T (15+logt)x10⁻³
B-17	--	1	3200	1760	1.0	6.9	3200	1760	1140	2671	1.570	66.0
B-24	--	1	2800	1538	2.0	13.8	2800	1538	1500	6812	3.708	59.2

TABLE II-3. Summary of Tungsten-25% Re Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter T (15+logt)x10⁻³
S-3	3.5-75002	48	3200	1760	5.0	34.4	3200	1760	12	45	6.03	58.9
S-4	3.5-75002	45	3200	1760	3.0	20.7	3200	1760	25	97	5.22	60.0
S-6	3.5-75002	1	3200	1760	0.5	3.4	3200	1760	***	253	0.090	***
S-8	3.5-75002	1	3200	1760	1.5	10.3	3200	1760	315	1306	5.113	64.0
S-55A	3.5-75002	1	2550	1400	10	68.9	1600	869	--	200	0.005	--
S-55B	3.5-75002		--		10	68.9	1650	900	--	203	0.005	--
S-55C	3.5-75002		--		10	68.9	1700	927	--	196	0.008	--
S-55D	3.5-75002		--		10	68.9	1750	954	--	241	0.018	--
S-55E	3.5-75002		--		10	68.9	1800	980	--	257	0.035	--
S-61A	3.5-75002		--		15	100.4	1600	869	--	235	0.008	--
S-61B	3.5-75002		--		15	100.4	1650	900	--	169	0.022	--
S-61C	3.5-75002		--		15	100.4	1700	927	--	196	0.038	--
S-61D	3.5-75002		--		15	100.4	1750	954	--	200	0.058	--
S-61E	3.5-75002		--		15	100.4	1800	980	--	194	0.078	--

***Insufficient creep to extrapolate

TABLE II-4. Summary of Sylvania A Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter T (15+logt) x10⁻³
S-12	--	2	3200	1760	5.0	34.4	3200	1760	35	170	5.25	60.6
S-15	--	2	3200	1760	3.0	20.7	3200	1760	250	907	5.862	63.7

TABLE II-5. Summary of AS-30 Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M^2	Test Temperature °F	Test Temperature °C	1/2% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1/2% Creep Larson-Miller Parameter $T\ (15+\log t) \times 10^{-3}$
B-2	C5	As-Rolled			12.0	82.7	2000	1093	390	806	1.020	43.3
B-6	C5	As-Rolled			11.0	75.8	2000	1093	450	1192	1.016	43.5
B-7	C5	As-Rolled			8.0	55.1	2200	1204	115	230	1.025	45.4

Table II-6. Summary of Cb-132M Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1/2% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1/2% Creep Larson-Miller Parameter T (15+logt) x10⁻³
B-13	KC-1454	1	3092	1700	20.0	138.0	2056	1125	275	568	1.170	43.8
B-14	KC-1454	1	3092	1700	16.3	82.3	2056	1125	340	691	1.026	44.0
B-15	KC-1454	1	3092	1700	7.4	51.0	2256	1236	250	596	1.100	47.2

TABLE II-7. Summary of TZM Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1/2% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1/2% Creep Larson-Miller Parameter T (15+logt)x10⁻³
B-1	7502	1	2200	1204	12.6	86.5	2130	1165	605	646	1.105	46.1
B-3	7502	1	2200	1204	10.0	68.9	2000	1095	14,200*	10,048	0.375	47.1
B-29	7502	1	2200	1204	41.0	282.0	2000	1095	100	664	6.215	41.8
B-35	7502	1	2200	1204	44.0	303.0	1800	982	7000	7659	0.535	42.6
B-4	7502	1	2200	1204	10.0	68.9	2000	1095	25,000*	10,012	0.368	47.7
	Plus	1	2850	1566								
B-16	KDTZM-1175	1	2300	1260	23.4	161.0	1855	1013	62,500*	4376	0.035	45.8
B-18	KDTZM-1175	1	2300	1260	55.0	379.0	1600	871	60,000*	2159	0.018	40.7
B-21	KDTZM-1175	1	2300	1260	65.0	448.0	1600	871	15,000*	1630	0.085	39.5
B-25	KDTZM-1175	1	2300	1260	44.0	303.0	1800	982	50,000*	10,152	0.182	44.5
B-38	KDTZM-1175	1	2300	1260	22.0	151.0	2000	1093	16,293	**	**	47.1
B-34	7463	1/2	2250	1232	41.0	282.0	2000	1093	790	1440	1.658	44.0

*Extrapolated data

**Test in progress

TABLE II-8. Summary of Cb Modified TZM Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1/2% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1/2% Creep Larson-Miller Parameter T (15+logt) x10⁻³
B-23A	4305-4	1	2500	1371	20.0	138.0	2000	1093	20,000*	686	0.032	47.5
B-23B	4305-4	-	--	--	28.0	193.0	2000	1093	10,000*	307	0.028	46.7
B-23C	4305-4	-	--	--	40.0	276.0	2000	1093	630*	185	0.188	43.8
B-23D	4305-4	-	--	--	46.0	317.0	1800	982	4000*	403	0.078	42.0
B-23E	4305-4	-	--	--	34.0	234.0	2100	1149	1000*	329	0.170	46.1
B-27	4305-4	1	2500	1371	41.0	282.0	2000	1093	1090	1584	1.040	44.5

*Extrapolated

TABLE II-9. Summary of TZC Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1/2% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1/2% Creep Larson-Miller Parameter T (15+logt) x10⁻³
B-8A	M-80	1	3092	1700	18.0	124.0	2200	1204	1100	2128	1.060	48.3
B-10	M-80	1	3092	1700	17.0	117.0	2200	1204	2500	2749	0.545	48.9
B-9	M-80	1	3092	1700	20.0	138.0	2000	1093	10,408	16,002	0.670	46.8
B-11	M-80	1	3092	1700	25.0	172.0	1856	1013	75,000*	14,406	0.182	46.0
B-12	M-80	1	3092	1700	19.0	131.0	2056	1125	75,000*	14,239	0.280	49.2
B-20	M-91	1	3092	1700	20.0	138.0	2000	1093	3650	12,795	1.008	45.7
B-31	M-91	1	3092	1700	14.0	96.5	2200	1204	329	912	1.092	46.6
B-19	M-91	1	2300	1260	44.0	303.0	1800	982	1075	4604	1.015	41.1
B-28	M-91	1	2300	1260	28.0	193.0	2000	1093	1100	4214	1.138	44.4
B-30	M-91	1	2500	1371	22.0	152.0	2200	1204	70	259	1.280	44.8
B-32	M-91	1	2500	1371	20.0	138.0	1935	1057	14,400	16,130	0.535	45.9
B-33	M-91	1	2500	1371	22.0	152.0	1900	1038	7720	9697	0.585	44.6
B-36	4345	1	2500	1371	22.0	152.0	2000	1093	5940	8563	0.640	46.2
B-37	4345	1	2400	1316	22.0	152.0	2000	1093	8853	9020	0.500	46.3

*Extrapolated

TABLE II-10. Summary of T-222 Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T\ (15+\log t)\times10^{-3}$
S-13	AL-TA-43	1	3000	1649	12.0	82.7	2200	1204	560	1890	5.720	47.2
S-14	AL-TA-43	1	3000	1649	19.2	132.0	2056	1124	890	1314	1.685	45.1
S-20	AL-TA-43	1	2800	1538	12.0	82.7	2200	1204	405	1389	5.060	46.9

TABLE II-11. Summary of ASTAR 811C Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M^2	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter T $(15+\log t)\times 10^{-3}$
S-29	NASV-20-WS	.5	3600	1982	2.0	13.8	2600	1427	21,190	21,560	1.028	59.3
S-70	VAM-95	.25	3520	1940	20	138.0	2100	1148	3600*	983.4	0.342	47.5
S-71	VAM-95	.15	3600	1982	20	138.0	2100	1148	3600*	767.5	0.320	47.5
S-70A	VAM-95	-	--	--	15	103.0	2200	1204	6000*	655.8	0.108	50.0
S-71A	VAM-95	-	--	--	15	103.0	2200	1204	6000*	678.9	0.112	50.0
S-70B	VAM-95	-	--	--	10	69.0	2300	1263	6000*	1106.4	0.153	51.9
S-71B	VAM-95	-	--	--	10	69.0	2300	1263	6000*	1082.2	0.178	51.9
S-73	VAM-95	.33	3600	1982	15	103.0	2400	1316	435	720.5	1.860	50.5
S-74	650056	.33	3600	1982	15	103.0	2400	1316	825	1466.0	2.185	51.2
S-75	VAM-95	1.0	3000	1649	15	103.0	2400	1316	144	162.3	1.195	49.1
S-76	650056	.5	3600	1982	25	162.0	2175	1191	695	4962.5	15.088	47.0
S-77	650056	.5	3600	1982	10	69.0	2400	1316	5287	5907.9	1.150	53.6
S-78	650056	.5	3600	1982	5	35.0	2550	1399	5611	6210.4	1.210	56.6
S-79	VAM-95	5	3450	1800	15	103.0	2400	1316	542	714	1.378	50.8
S-81	VAM-95	24	3270	1700	15	103.0	2400	1316	560	666.5	1.330	50.8
S-85	650056	.5	3600	1982	20	138.0	2175	1191	5000*	**	**	
S-86	650056	.5	3600	1982	15	103.0	2300	1263	5500*	**	**	
S-87+	NASY-20	1	3000	1649	15	103.0	2400	1316	68	329	11.470	

*Extrapolated
**Test in progress
***Insufficient creep to extrapolate

+From G.E. Alkali Metal exposure program

TABLE II-12. Summary of T-111 Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter T (15+logt) x10⁻³
S-16	70616	1	2600	1427	8.0	55.1	2200	1204	725	1675	2.570	47.5
S-19	70616	1	3000	1649	8.0	55.1	2200	1204	2000	4870	3.368	48.7
S-21	70616	1	3000	1649	12.0	82.6	2200	1204	1140	3840	6.548	48.0
S-23	70616	1	3000	1649	12.0	82.6	2120	1160	3150	3698	1.225	47.7
S-22	70616	1	3000	1649	20.0	138.0	2000	1093	670	1099	2.010	43.8
S-24	70616	1	3000	1649	20.0	138.0	1860	1016	4730	4946	1.090	43.3
S-25	D-1670	1	3000	1649	15.0	103.0	2000	1093	1340	1584	1.210	44.6
S-26	D-1670	1	3000	1649	17.0	117.0	1800	982	9540	9624	1.030	42.9
S-25A	D-1670	1	3000	1649	1.5	10.3	2600	1427	1100*	482	0.632	55.2
S-28	D-1670	1	3000	1649	0.5	3.4	2600	1427	55,000*	**	**	60.0
S-27	D-1102	1	3000	1649	13.0	89.5	2000	1093	1880	3459	2.082	45.0
S-32	D-1102	1	3000	1649	5.0	34.4	2200	1204	4050	4322	1.042	49.5
S-40	D-1102	1	3000	1049	17.0	117.0	1800	982	8558	8717	1.028	42.8
S-33	65076	1	3000	1649	8.0	55.1	2200	1204	2850	2976	1.048	49.1
S-34	65076	1	3000	1649	11.0	75.8	2000	1093	10,800	10,875	1.010	46.9

*Extrapolated
**Test in progress

TABLE II-12. Summary of T-111 Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter T (15+logt)x10⁻³
S-37	6580	1	3000	1649	8.0	55.1	2200	1204	260	274	1.230	46.3
S-39	65080	1	3000	1649	13.0	89.5	1800	982	8202	8728	1.070	42.7
S-45	65080	1	3000	1649	3.0	20.0	2200	1204	554	697	1.165	47.1
S-30	65079	1	3000	1649	3.5	24.1	2400	1316	860	2137	2.372	51.3
S-31	65079	1	3000	1649	5.0	34.4	2200	1204	6160	6594	1.092	50.0
S-35	65079	1	3000	1649	5.0	34.4	2200	1204	5400	5522	1.048	49.9
S-42	65079	1	3000	1649	3.5	24.1	2300	1263	3810	4247	1.122	51.3
S-47	65079	1	3000	1649	24.0	165.0	1750	954	19,896	**	**	43.3
S-48	65079	1	3000	1649	2.4	165.0	2330	1275	5500	6284	1.200	52.3
S-50	65079	1	3000	1649	8.5	72.2	2000	1093	24,000*	5735	0.272	47.7
S-43	65079	1/4	3000	1649	18.0	124.0	2000	1093	1500*	361	0.108	44.7
S-44A	65079	1	3000	1649	9.5	65.5	2172	1189	3250*	467	0.152	48.7
S-44B	65079	1/4	3000	1649	3.3	22.7	2371	1299	2030*	335	0.168	51.9
S-44C	65079	1/4	3000	1649	18.0	124.0	2000	1093	1670*	1146	0.688	44.8
S-44D	65079	1/4	3000	1649	23.0	158.0	1800	982	14,650*	1391	0.112	43.3
S-59	D-1183	1	3000	1649	13.0	89.5	2000	1093	13,500*	**	**	47.1

*Extrapolated
**Test in progress

TABLE II-12. Summary of T-111 Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter T (15+logt)x10⁻³
S-60	D-1183	1	3000	1649	35.0	241.0	1600	870	8550	**	**	39.0
S-68	650028	1	3000	1649	1.0	6.9	2560	1403	2300	**	**	55.5
S-69	650028	1	3000	1649	30.0	207.0	1625	885	17,000*	**	**	
B-43	650028	1	3000	1649	20.0	138.0	2000	1093	1823	1840.8	1.012	44.8
B-44	650038	1	3000	1649	35.0	241.0	2000	16	1093	55.1	7.582	39.8
P-1	8049	1	3000	1649	19.0	131.0	2000	1093	2070	3649	2.142	45.1
S-80	650028	1	3000	1649	37.0	255.0	1300	704	***	3192.8	0.775	***
S-82A	650028	-	--	--	50.0	34.4	900	482	***	**	**	***
S-83	650028	1	3000	1649	45.0	31.0	1100	593	7	1177.1	2.945	24.8
S-84	650028	1	3000	1649	1.5	10.4	2400	1316	3000*	**	**	
S-41	65080	15	3000	1649	8.0	55.1	2200	1204	234	259	1.080	

*Extrapolated
**In progress
***Insufficient to extrapolate

TABLE II-13. Summary of T-111 Progressive Stress Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress Rate PSI/Hr	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep
S-36	65080	1	3000	1649	16	2200	1204	600	624	1.120
S-38	65080	1	3000	1649	1	2200	1204	3830	4686	1.562
S-46	65079	1	3000	1649	16	2200	1204	1000*	761	0.225
S-49	65079	1	3000	1649	20	1800	982	1660	1964	5.125
S-51	D-1183	1	3000	1649	16	2200	1204	1080	1274	5.823
S-52	65079	1	3000	1649	13	2000	1093	1700*	1657	1.150
S-53	65079	1	3000	1649	5	2200	1204	2240	2970	5.292
S-54	65079	1	3000	1649	5	2000	1093	3850	6506	6.478
S-56	65079	1	3000	1649	5	1800	982	5500	6375	5.280
S-57	65079	1	3000	1649	1	2200	1204	7748	8833	1.510
S-62	65079	1	3000	1649	2	2000	1093	8300	8599	1.150

*Extrapolated

TABLE II-14. Summary of Pure Ta Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter T (15+logt) x10⁻³
B-39A	B-1962	1	1832	1000	13.6	93.7	1100	596	31	32	1.020	25.8
B-39B	B-1962	1/4	1832	1000	11.6	79.9	1100	596	603*	264	0.542	27.8
B-39C	B-1962	1/4	1832	1000	10.1	69.5	1183	639	463*	282	0.635	29.0
B-40A	B-1962	1	1832	1000	7.0	48.3	1350	732	9	9	1.000	28.9
B-40B	B-1962	1/4	1832	1000	4.9	33.8	1350	732	6600*	1386	0.300	34.0
B-41	B-1962	1	1832	1000	11.1	76.5	1100	596	144	160	1.078	26.7
B-42A	B-1962	1	1832	1000	4.0	27.5	1350	732	170	186	1.015	31.2
B-42B	B-1962	1/4	1832	1000	4.0	27.5	1350	732	2070	1775	0.892	33.1
B-45	60249	0.1	2290	1255	4.0	27.5	1350	732	***	69.6	0.002	***
B-45B	60249	0.1	2290	1255	8.0	55.0	1350	732	520	1800	1.823	32.0
B-46	60249	0.1	2290	1255	6.5	44.8	1350	732	5600*	155.8	0.215	34.0
B-47++	60249	0.1	2290	1255	16 psi/hour		1350	732	544	548.3	1.050	--
B-47A	60249	-	--	--	8.0	55.0	1350	732	714	907	1.190	32.3
B-48A+	60249	0.1	2290	1255	6.5	44.8	1450	788	252	2371	2.885	33.2

*Extrapolated
**Test in progress
***Insufficient creep to extrapolate

+welded
++Progressive stress

TABLE II-14. Summary of Pure Ta Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M^2	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T\ (15+\log t)\times10^{-3}$
B-48B+	60249	-	--	--	7.5	52.3	1450	788	150	1177.2	3.212	32.8
B-49	60249	0.1	2290	1255	6.5	44.8	1450	788	92	**	**	32.4
B-49A	60249	-	--	--	7.5	52.3	1450	788	180	1363.9	3.282	33.0
B-49B	60249	-	--	--	9.0	62.1	1450	788	24	497.8	5.698	31.3
B-51	60379	0.1	2290	1255	6.5	44.8	1350	732	26	**	**	29.8
B-52	60065	0.1	2290	1255	6.5	44.8	1350	732	17,000*	2062	0.115	34.8
B-53	60381	0.1	2290	1255	6.5	44.8	1350	732	7500*	**	**	33.9
P-2	818072	++	++	++	6.5	44.8	1350	732	1.6	649.7	4.685	27.5
P-3	B-1960	++	++	++	6.5	44.8	1350	732	60	**	**	30.4
P-4	B-1960	++	++	++	6.5	44.8	1350	732	30	**	**	29.8
P-5-	B-1960	++	++	++	6.5	44.8	1350	732	37,000*	**	**	

*Extrapolated
**Test in progress
+Welded
++Not Available
-Prestructured 30% in tension prior to test

TABLE II-15. Summary of Ta-10W Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter T (15+logt)x10⁻³
S-58A	630002	1	3000	1649	20	38.0	2100	1148	285	308	1.125	44.7
S-58B	630002	1/4	3000	1649	11.5	79.3	2210	1209	770*	410	0.572	47.7
S-58C	630002	1/4	3000	1649	6.2	42.7	2320	1268	2200*	700	0.330	51.0
S-58D	630002	1/4	3000	1649	3.5	24.1	2430	1332	10,200*	1290	0.202	54.9
S-64	630002	1	3000	1649	16	111.0	2000	1093	250	266	1.060	42.8
S-66	630002	1	3000	1649	16	111.0	2000	1093	135	550	5.150	42.1
S-67	630002	1	3000	1649	12	82.9	2000	1093	5227	6098	1.270	46.0

*Extrapolated
**Test in progress

TABLE II-16. Summary of T-111 Progressive Temperature Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Starting Test Temperature °F	Starting Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	Rate of Temperature Decrease F°/hr
S-65	65079	1	3000	1649	7	48.2	2400	1316	--	1850	0.105	0.6
S-72	650028	1	3000	1649	7	48.2	2400	1316	370	1322.1	1.282	0.3
S-82	650028	1	3000	1649	31	214.0	1900	1038	235	2013.8	1.180	0.5

APPENDIX III

CREEP CURVES

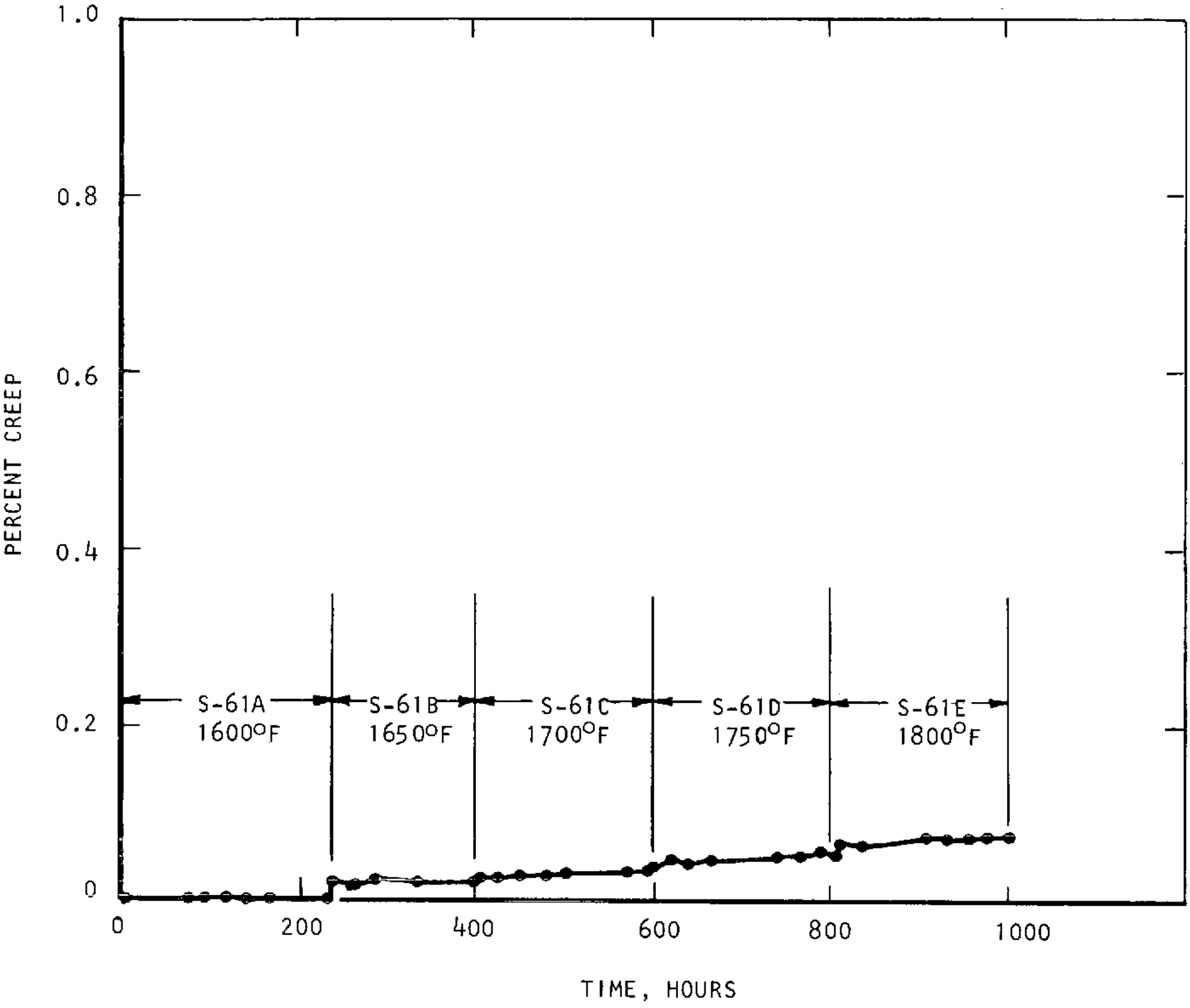

FIGURE III-1. CREEP TEST DATA, W-25%Re HEAT NO. 3.5-750002 STRESS RELIEVED 1 HOUR AT 2550°F (1400°C), TESTED AT VARIOUS TEMPERATURES AT 15 KSI (10.4×10^7 N/M^2), TEST NOS S-61A, B, C, D AND E IN A SEQUENTIAL TEST PROGRAM, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR.

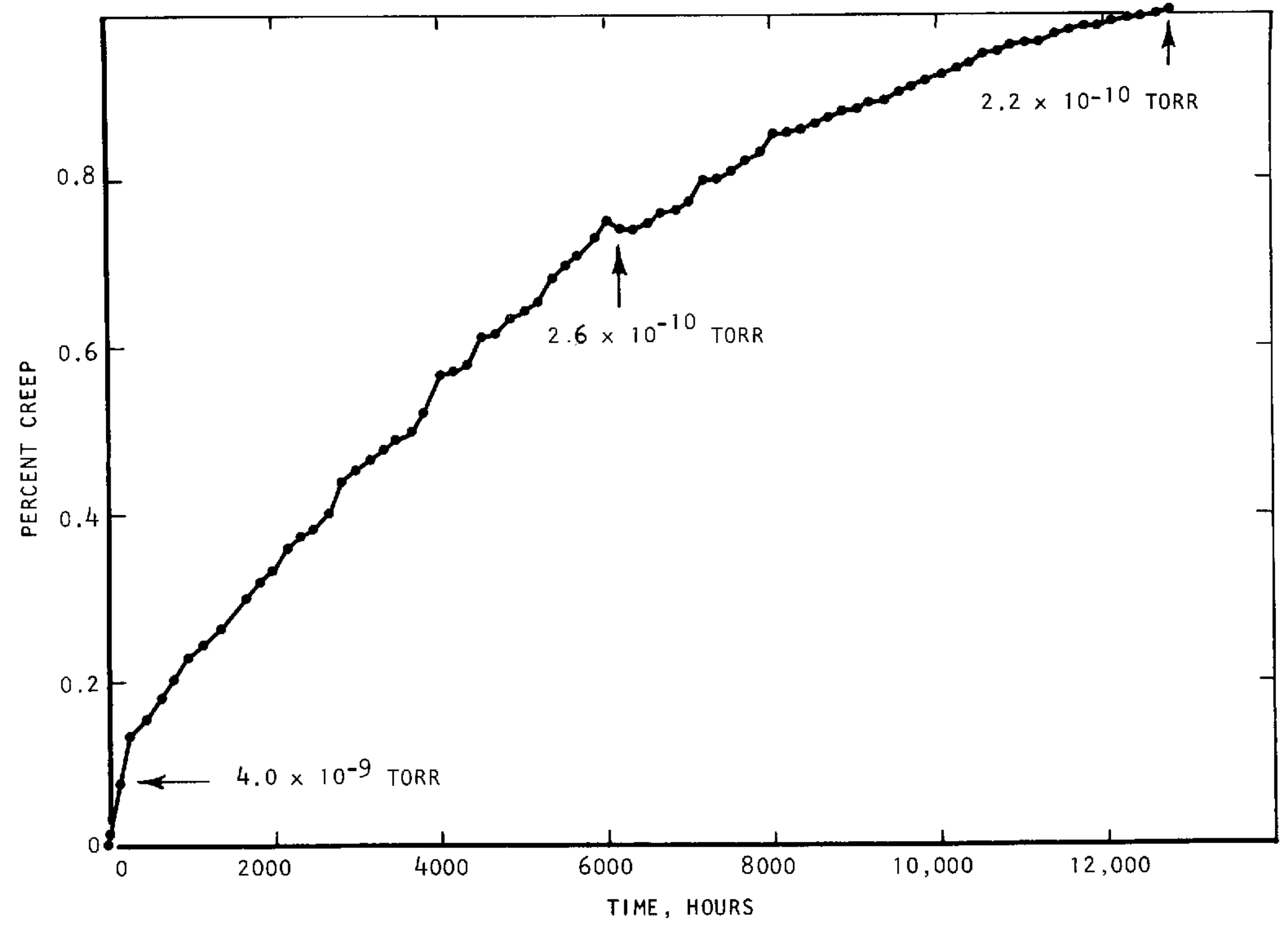

FIGURE III-2. CREEP TEST DATA, TZC HEAT NO. M-91 ANNEALED 1 HOUR AT 3092°F (1700°C), TESTED AT 2000°F (1093°C) AND 20 KSI (138 MN/M^2), TEST NO. B-20, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

64

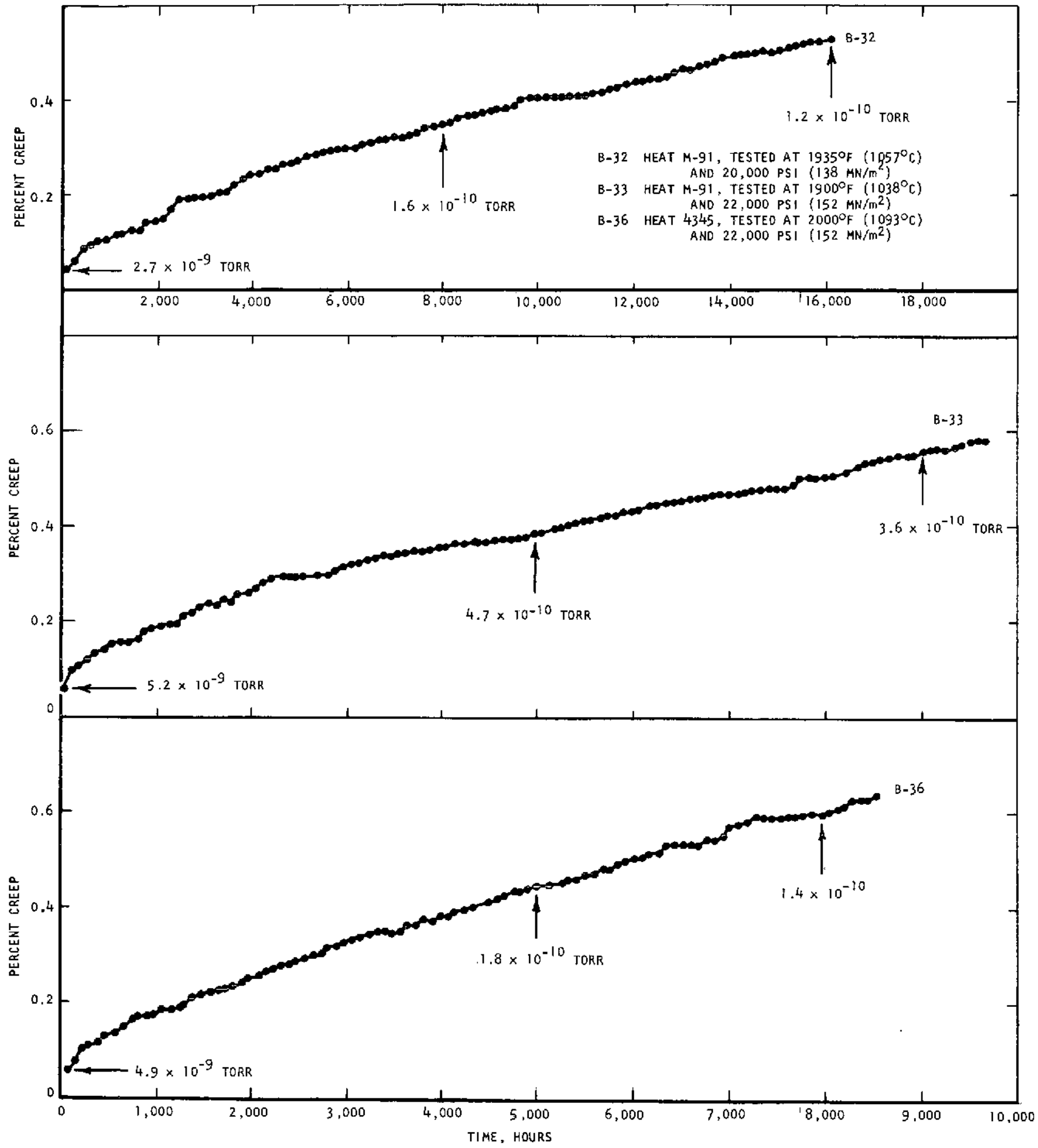

FIGURE III-3. CREEP TEST DATA, STRESS RELIEVED 1 HOUR AT 2500°F (1371°C) TEST NOS. B-32, B-33 AND B-36, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

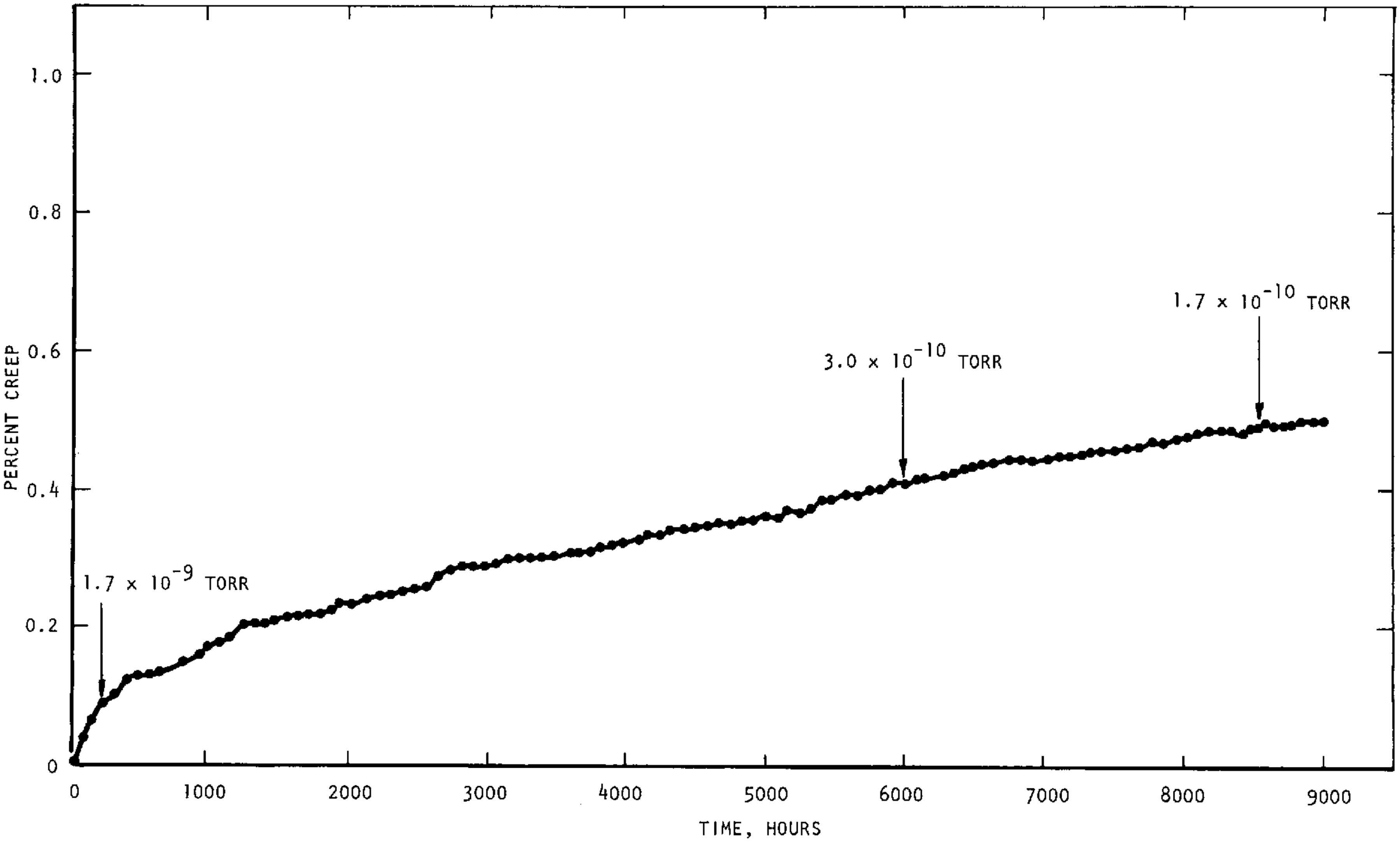

FIGURE III-4. CREEP TEST DATA, TZC HEAT NO. 4345 STRESS RELIEVED 1 HOUR AT 2400°F (1316°C), TESTED AT 2000°F (1093°C) AND 22 KSI (15.2×10^7 N/M^2), TEST NO. B-37, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

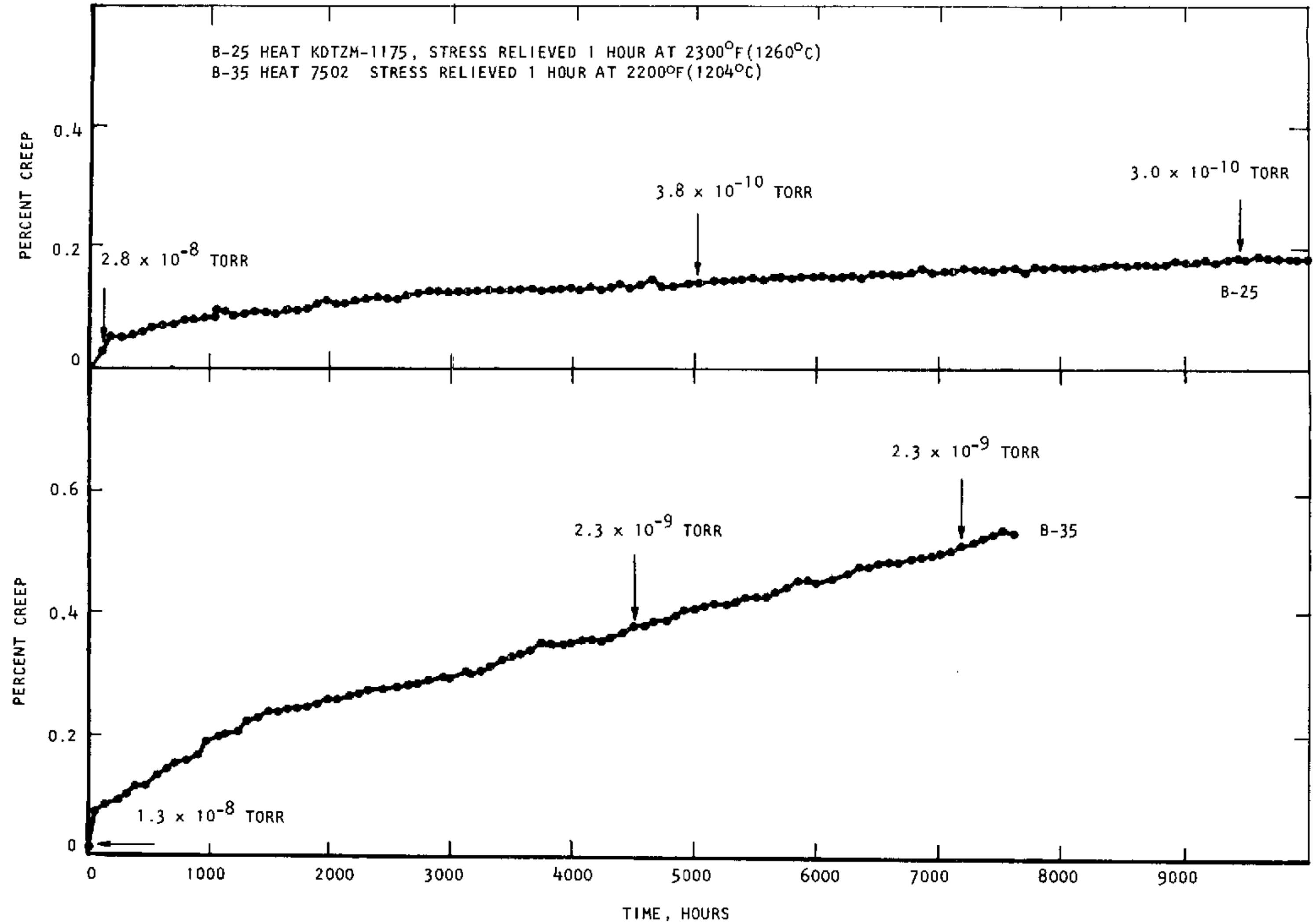

FIGURE III-5. CREEP TEST DATA, TZM, TESTED AT 1800°F (982°C) AND 44 KSI (303 MN/M^2), TEST NOS. B-25 AND B-35, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

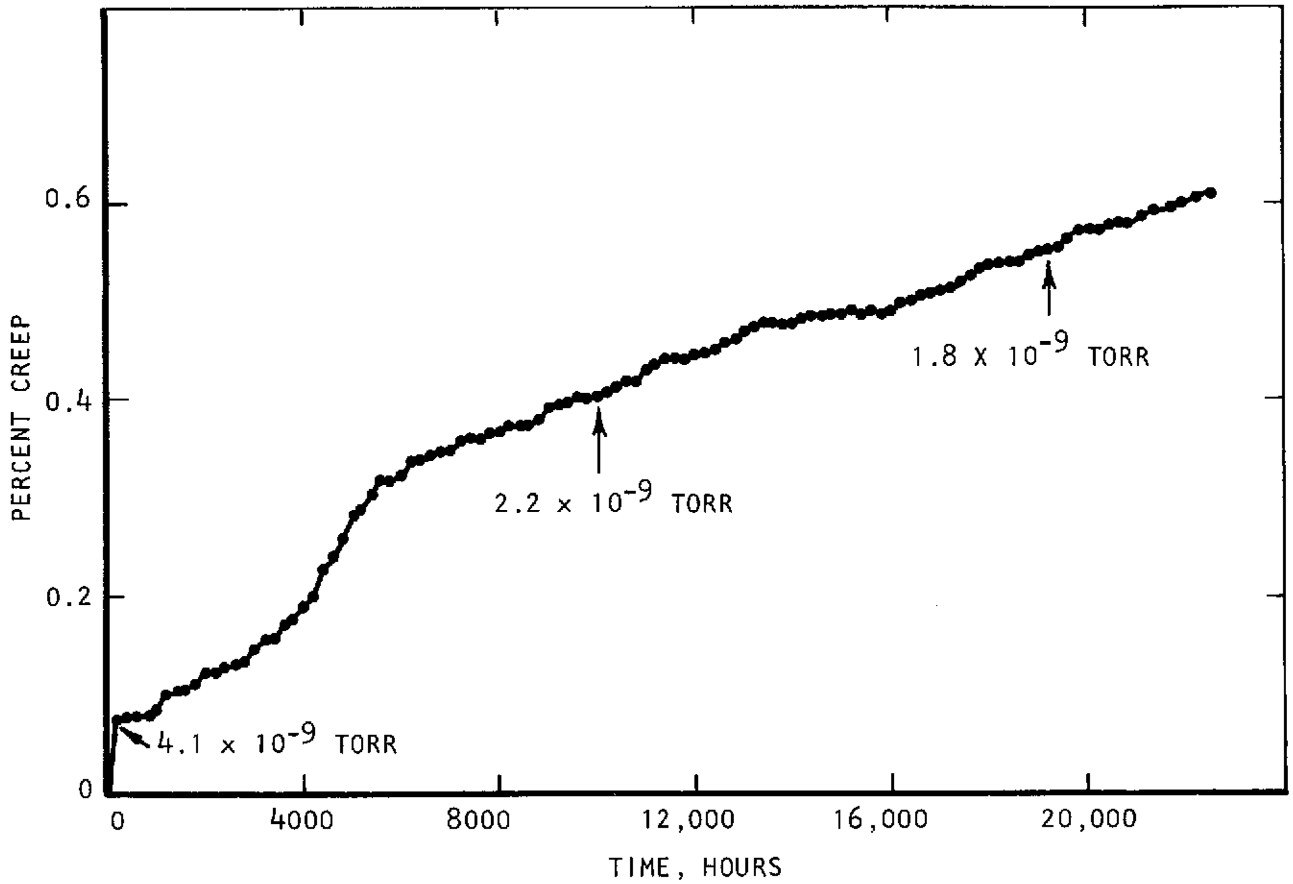

FIGURE III-6. CREEP TEST DATA, TZM HEAT NO. KDTZM-1175 STRESS RELIEVED 1 HOUR AT 2300°F (1260°C), TESTED AT 2000°F (1093°C) AND 22 KSI (151 MN/M^2), TEST NO. B-38, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

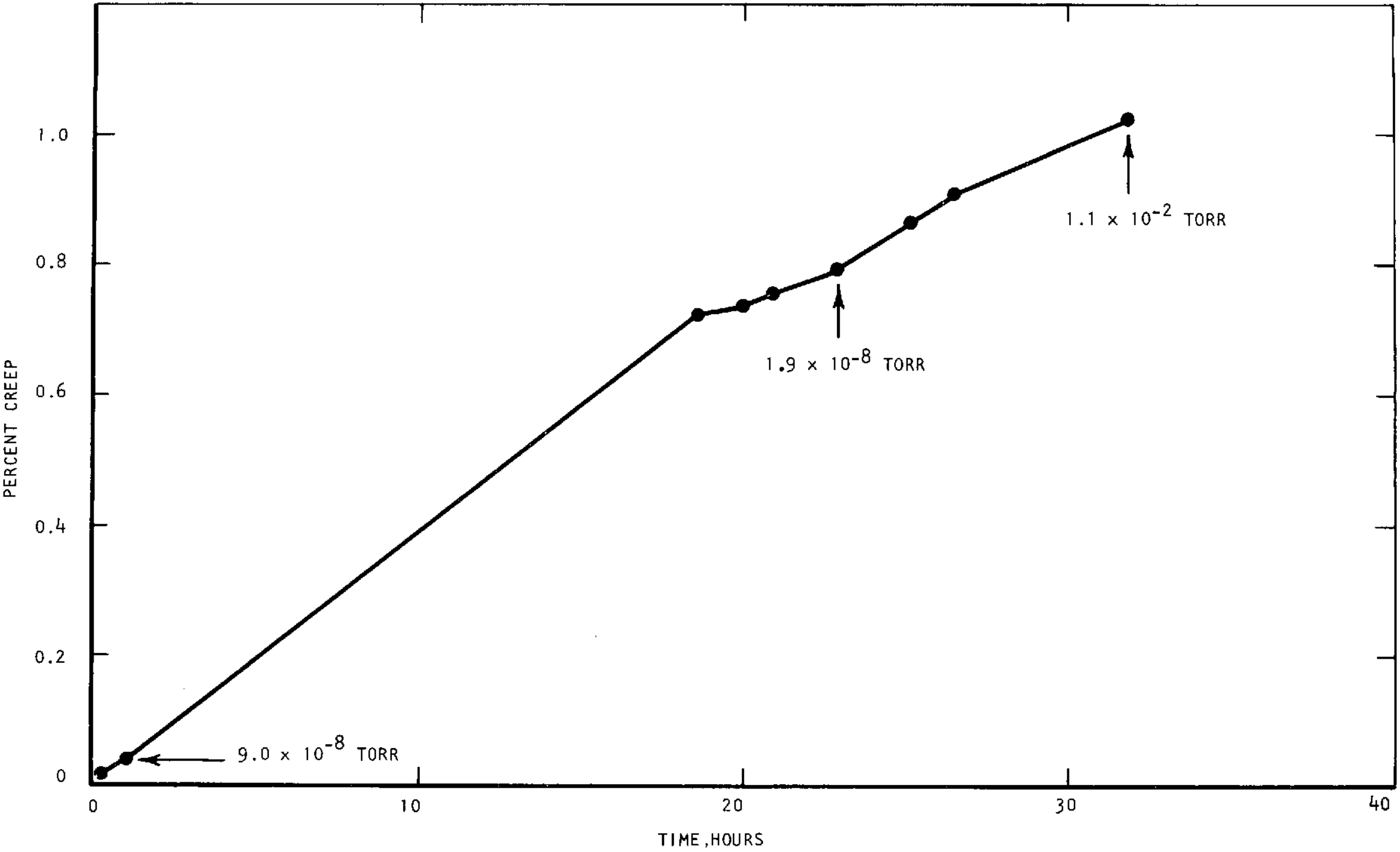

FIGURE III-7. CREEP TEST DATA, PURE TANTALUM HEAT NO. B-1962 ANNEALED 1 HOUR AT 1832°F (1000°C), TESTED AT 1100°F (596°C) AND 13.6 KSI (93.7 MN/M^2), TEST NO. B 39A IN A SEQUENTIAL TEST SERIES TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

B-39B TESTED AT 1100°F(596°C) AND 11,600 PSI (79.9 MN/m^2)
B-39C TESTED AT 1100°F(596°C) AND 10,100 PSI (69.5 MN/m^2)

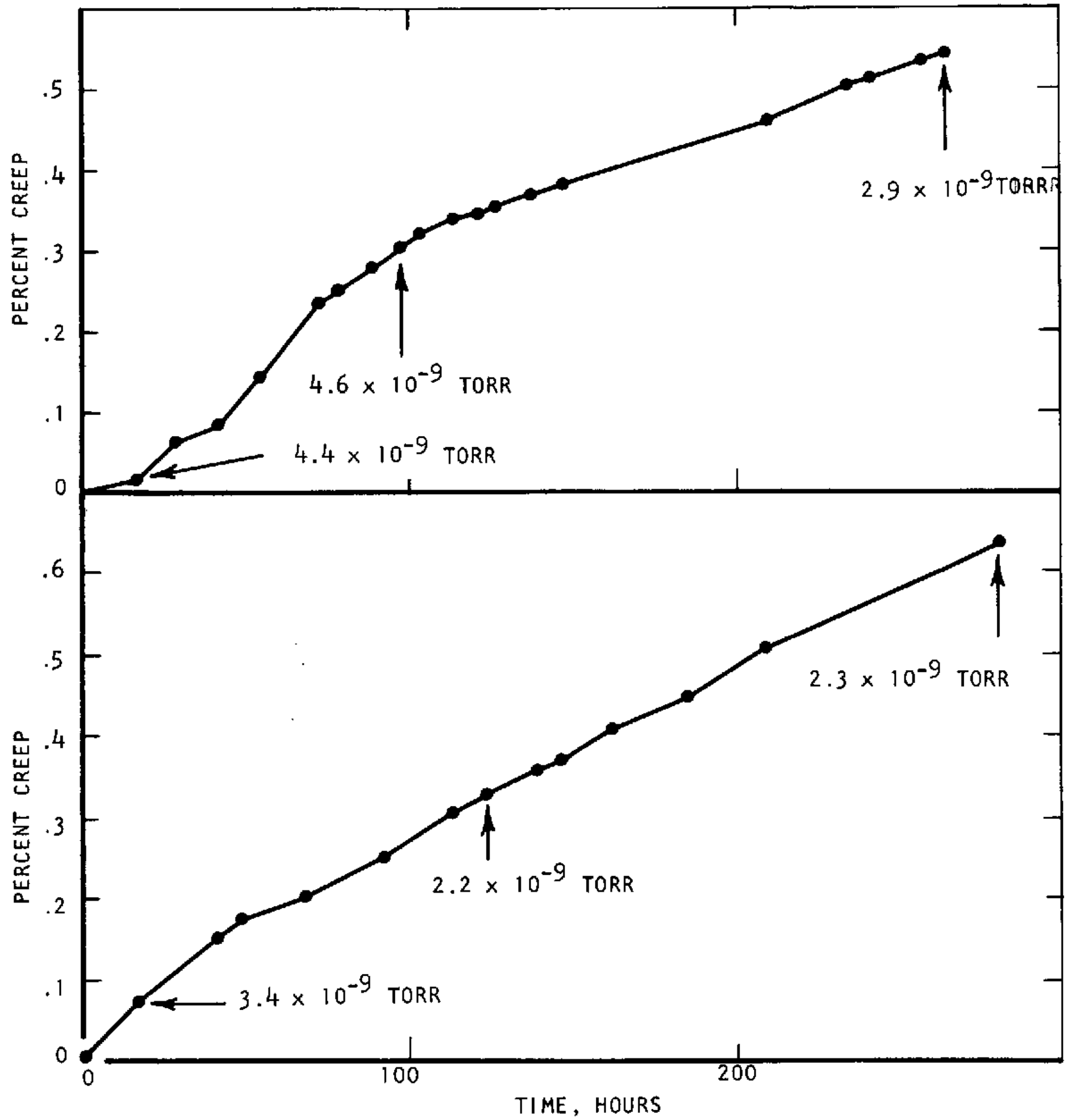

FIGURE III-8. CREEP TEST DATA, PURE TANTALUM HEAT NO. B-1962 INTERSEQUENCE ANNEALED 1/4 HOUR AT 1832°F (1000°C), TEST NOS. B39B AND B39C IN SEQUENTIAL TEST SERIES, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

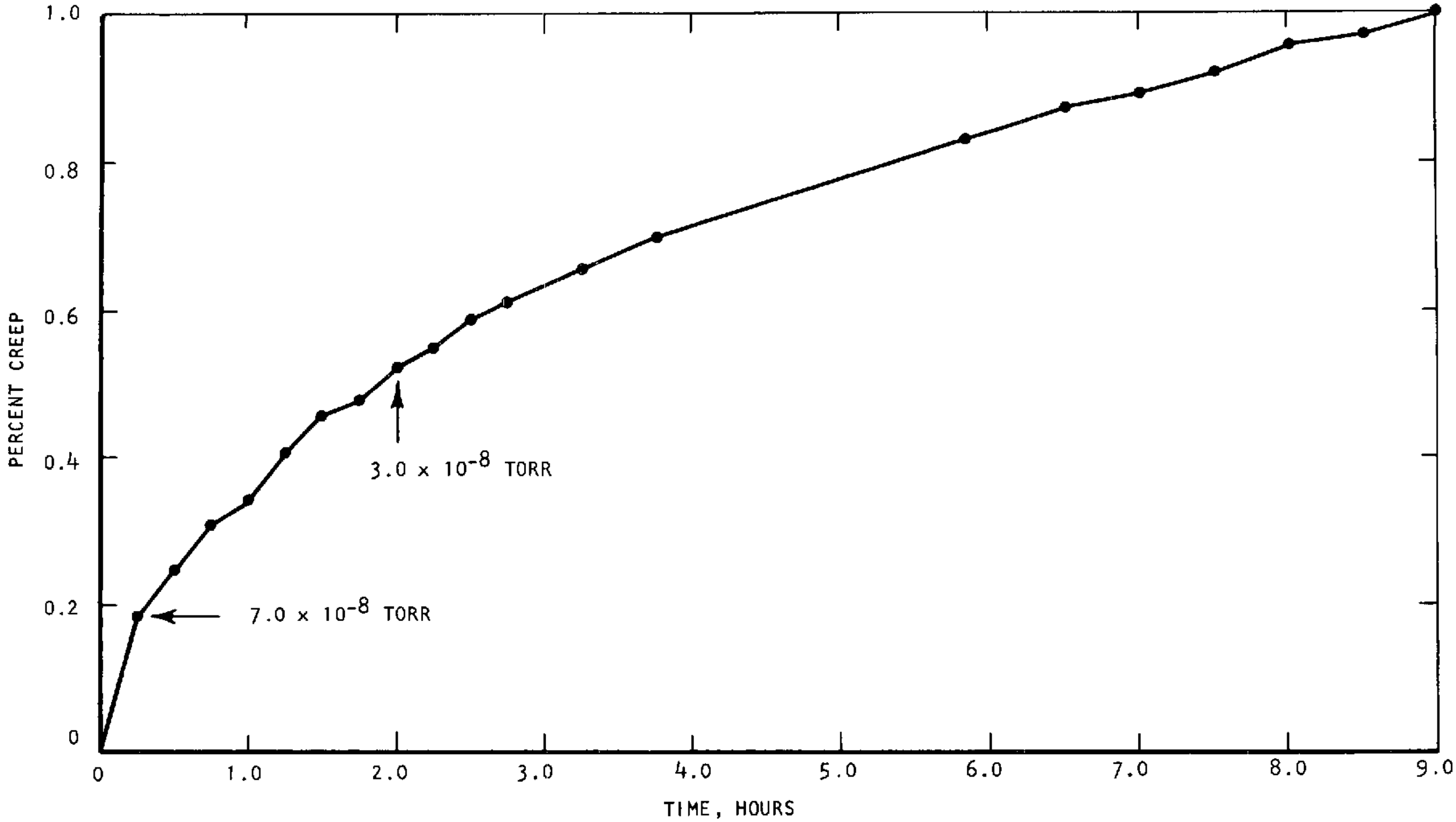

FIGURE III-9. CREEP TEST DATA, PURE TANTALUM HEAT NO. B-1962 ANNEALED 1 HOUR AT 1832°F (1000°C) TESTED AT 1350°F (732°C) AND 7.0 KSI (48.3 MN/M^2), TEST NO. B40A IN A SEQUENTIAL TEST SERIES, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

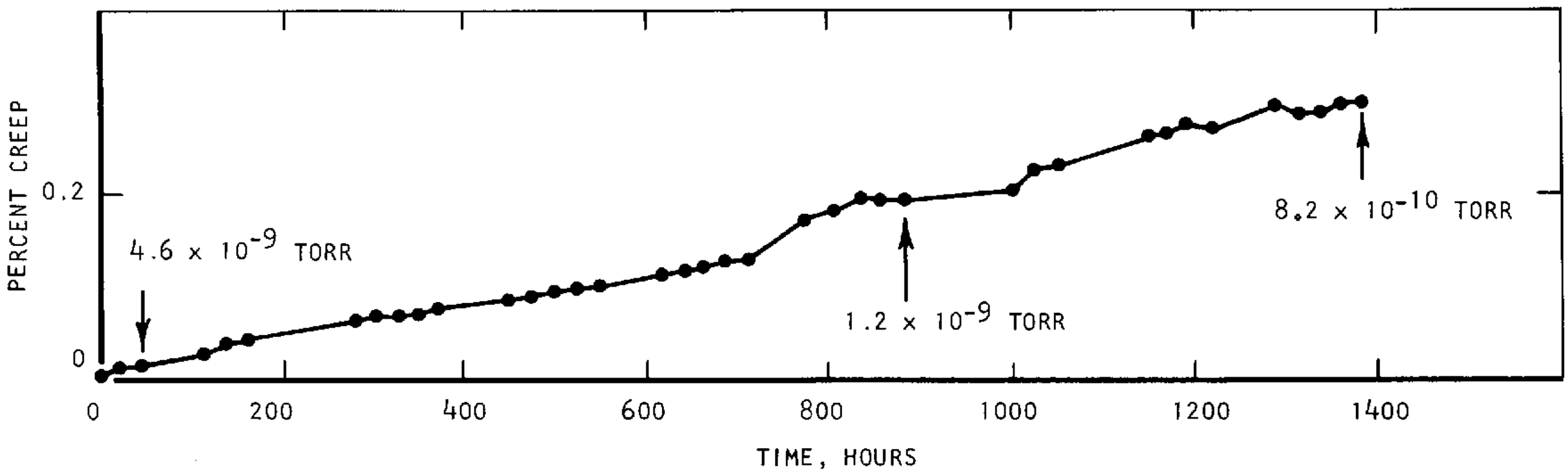

FIGURE III-10. CREEP TEST DATA, PURE TANTALUM HEAT NO. B-1962, INTERSEQUENCE ANNEALED 1/4 HOUR AT 1832°F (1000°C), TESTED AT 1350°F (732°C) AND 4.9 KSI (33.8 MN/M^2), TEST NO. B40B IN A SEQUENTIAL TEST SERIES, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

118 C

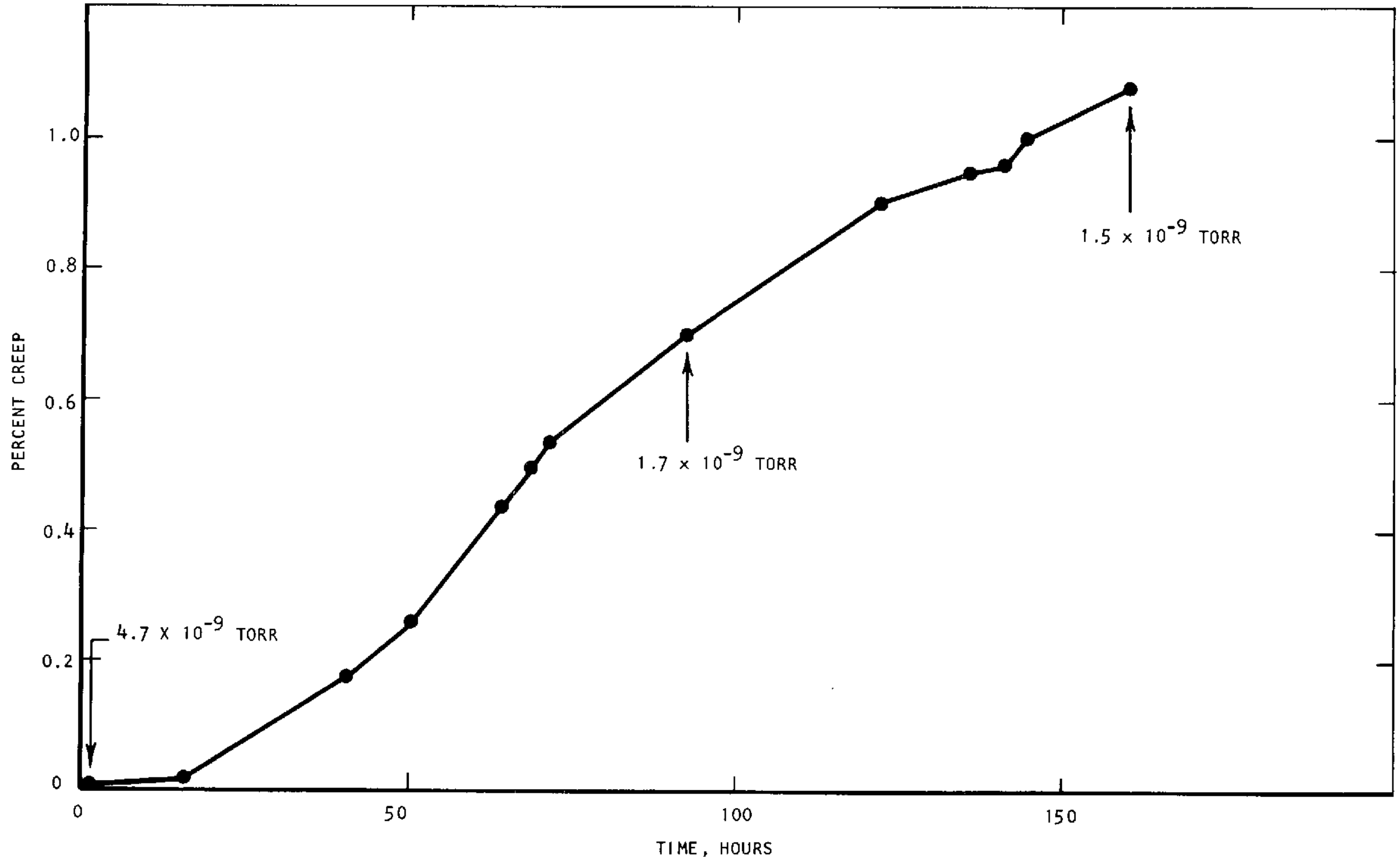

FIGURE III-11 CREEP TEST DATA, PURE TANTALUM HEAT NO. B-1962 ANNEALED 1 HOUR AT 1832°F (1000°C), TESTED AT 1100°F (596°C) AND 11.1 KSI (76.5 MN/M^2), TEST NO. B41, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

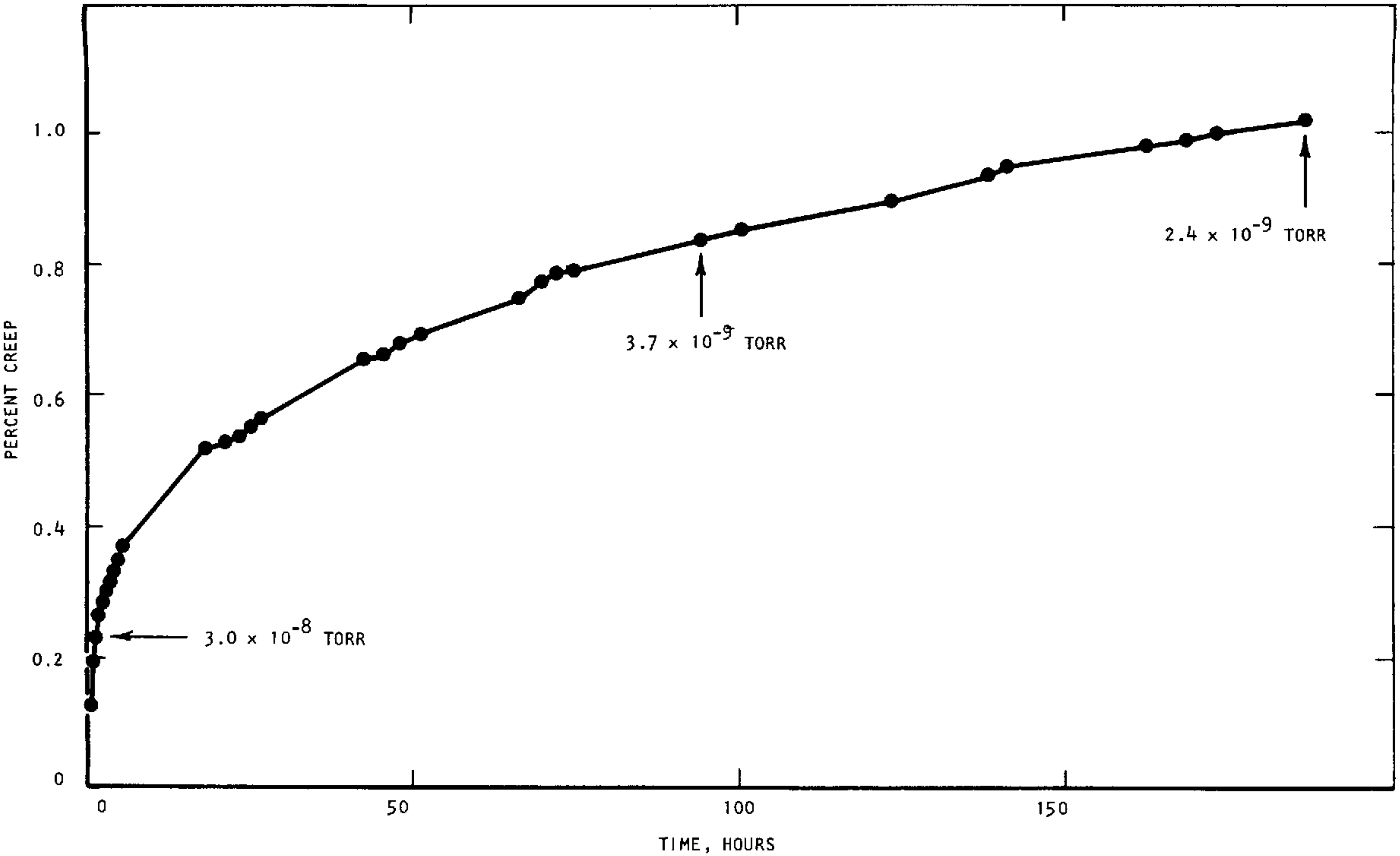

FIGURE III-12. CREEP TEST DATA, PURE TANTALUM HEAT NO. B-1962 ANNEALED 1 HOUR AT 1832°F (1000°C), TESTED AT 1350°F (732°C) AND 4.0 KSI (27.5 MN/M^2), TEST NO. B42A IN A SEQUENTIAL TEST SERIES, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

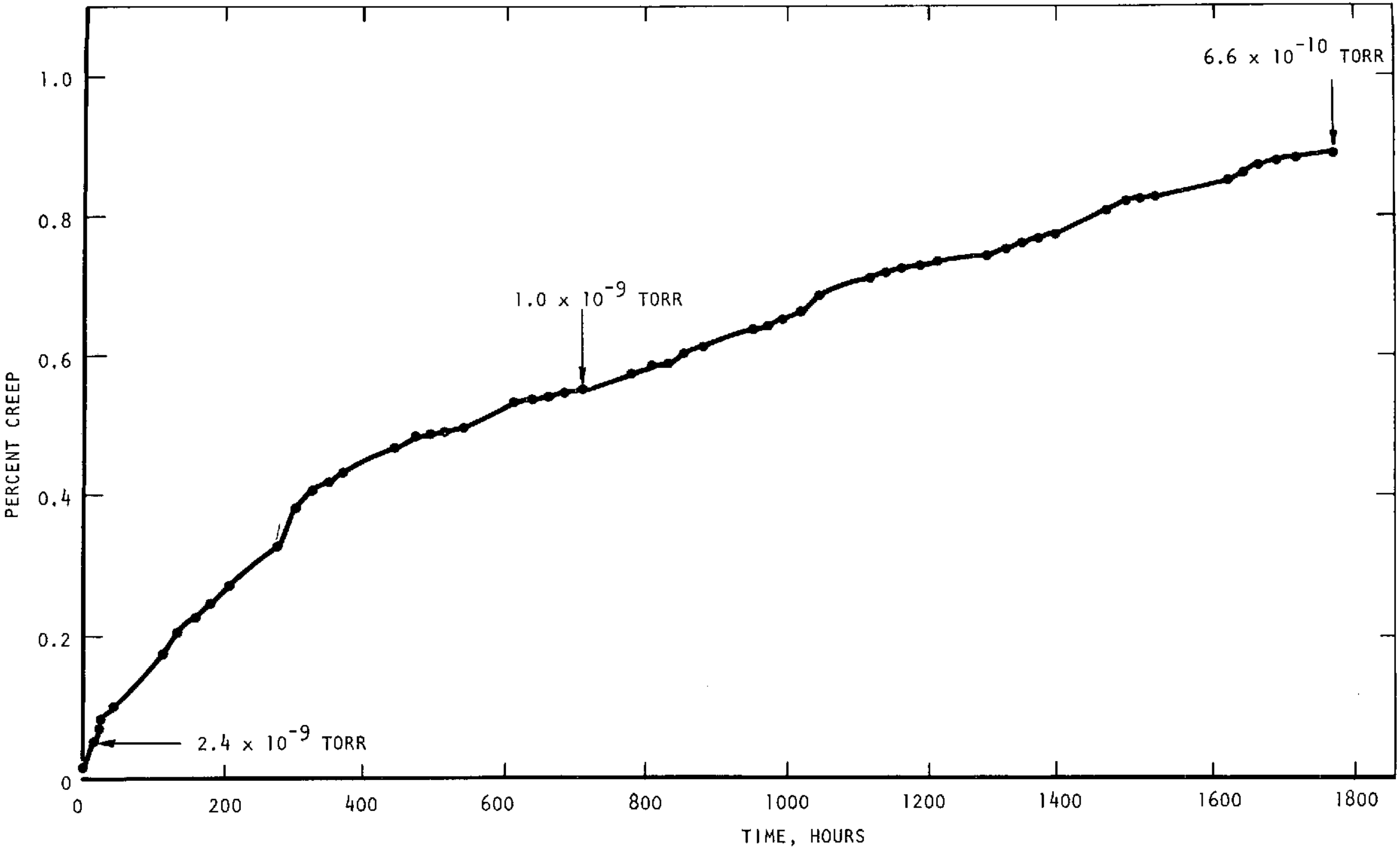

FIGURE III-13. CREEP TEST DATA, PURE TANTALUM ANNEALED 1/4 HOUR AT 1832°F (1000°C), TESTED AT 1350°F (720°C) AND 4.0 KSI (2.75 x 10^7 N/M^2), TEST NO. B-42-B IN SEQUENTIAL TEST PROGRAM, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

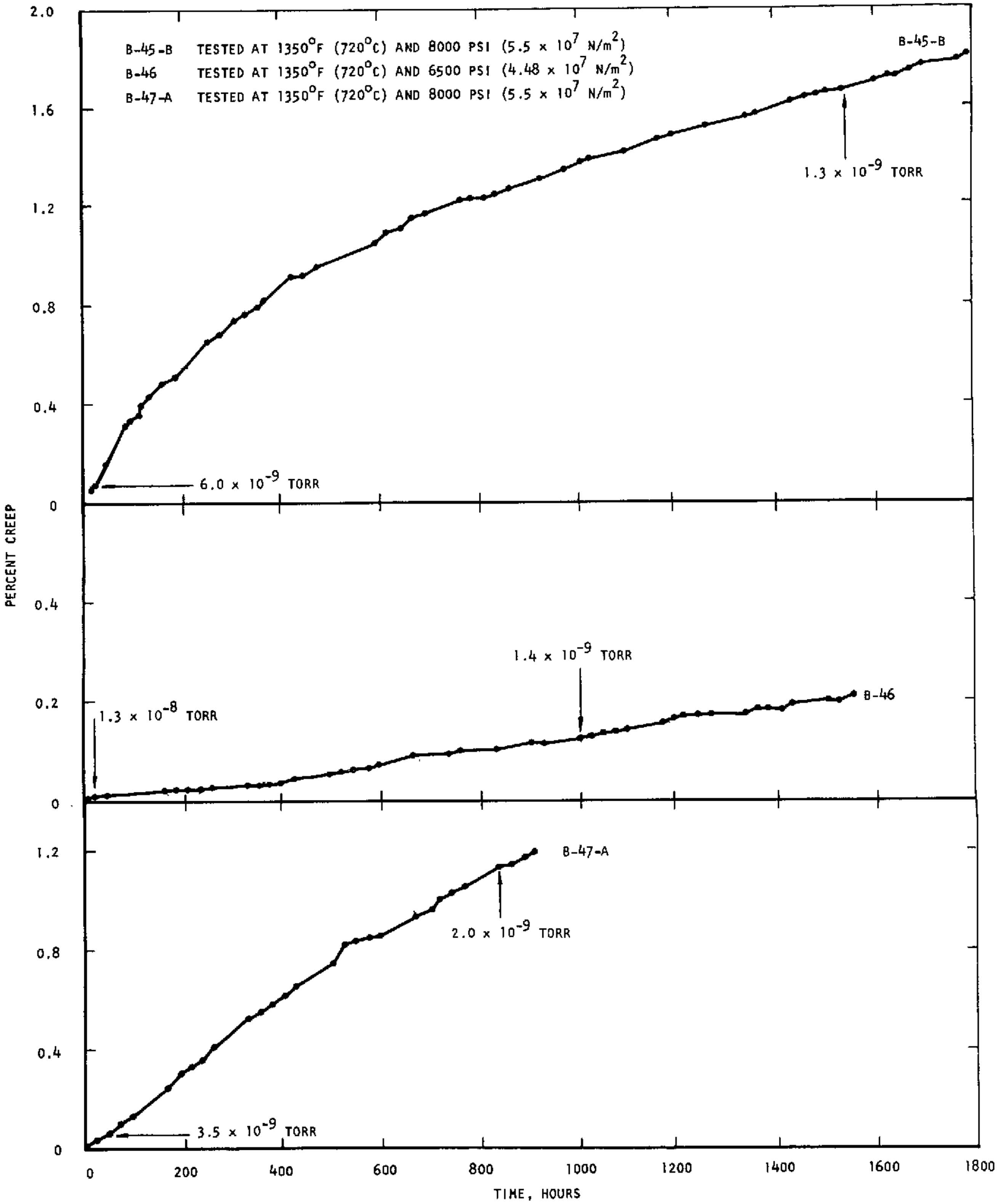

FIGURE III-14. CREEP TEST DATA, PURE TANTALUM HEAT NO. 60249 ANNEALED 0.1 HOUR AT 2290°F (1258°C), TEST NOS B-45B, B-46, and B-47A TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

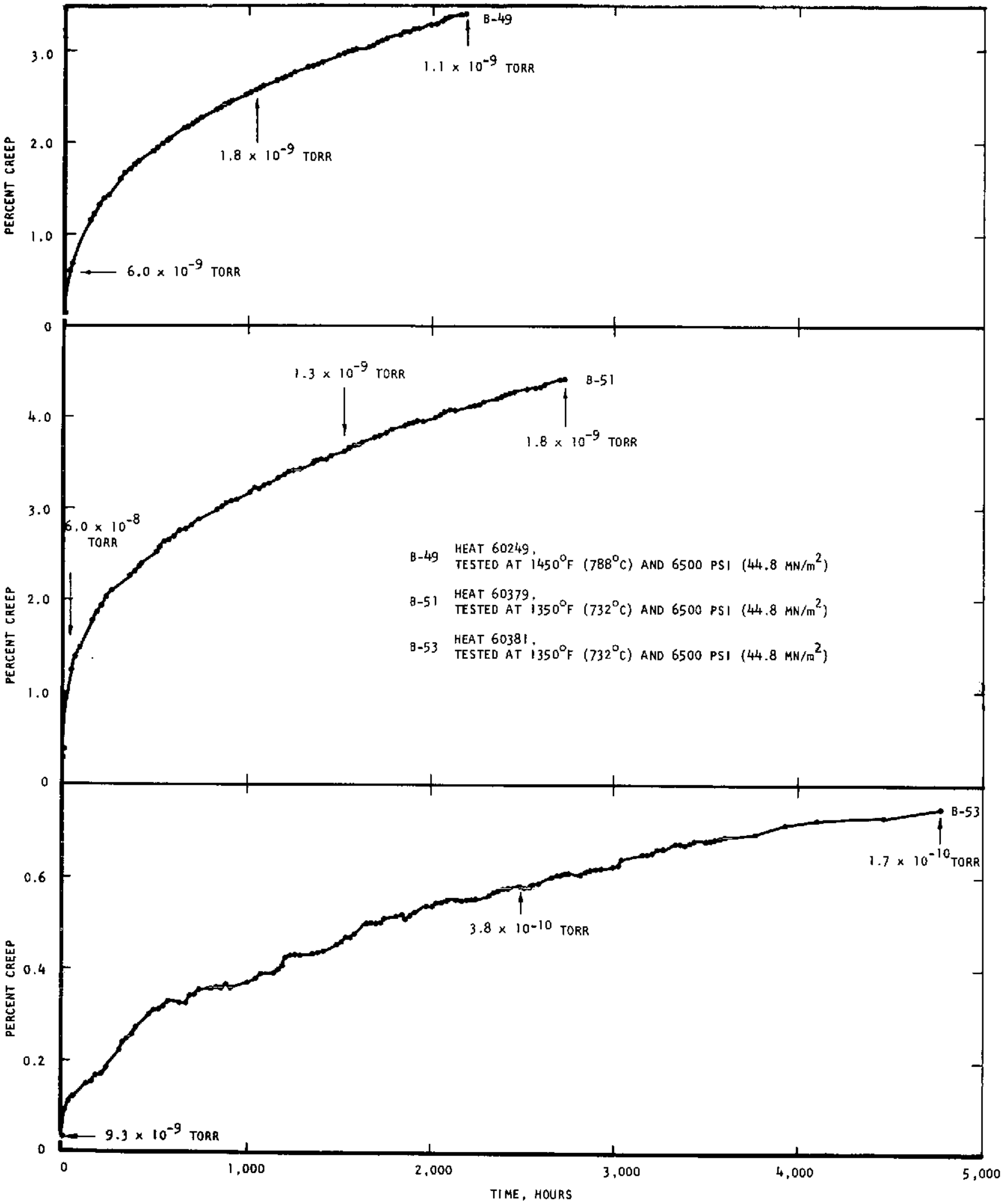

FIGURE III-15. CREEP TEST DATA, PURE TANTALUM ANNEALED 0.1 HOUR AT 2290°F (1255°C), TEST NOS. B-49, B-51 AND B-53, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

120 C

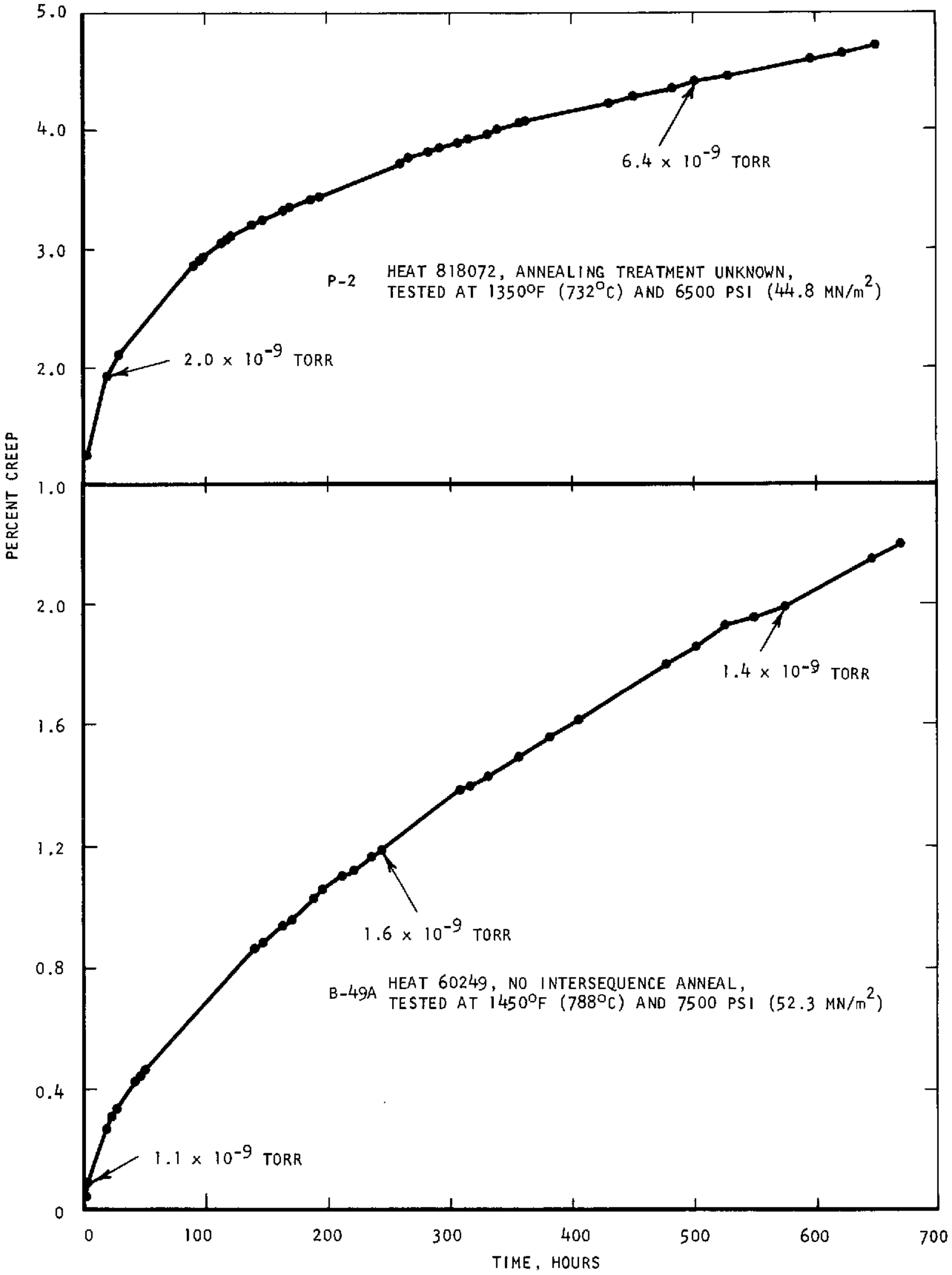

FIGURE III-16. CREEP TEST DATA, PURE Ta, TEST NOS. P-2 AND B-49A, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

5725 B

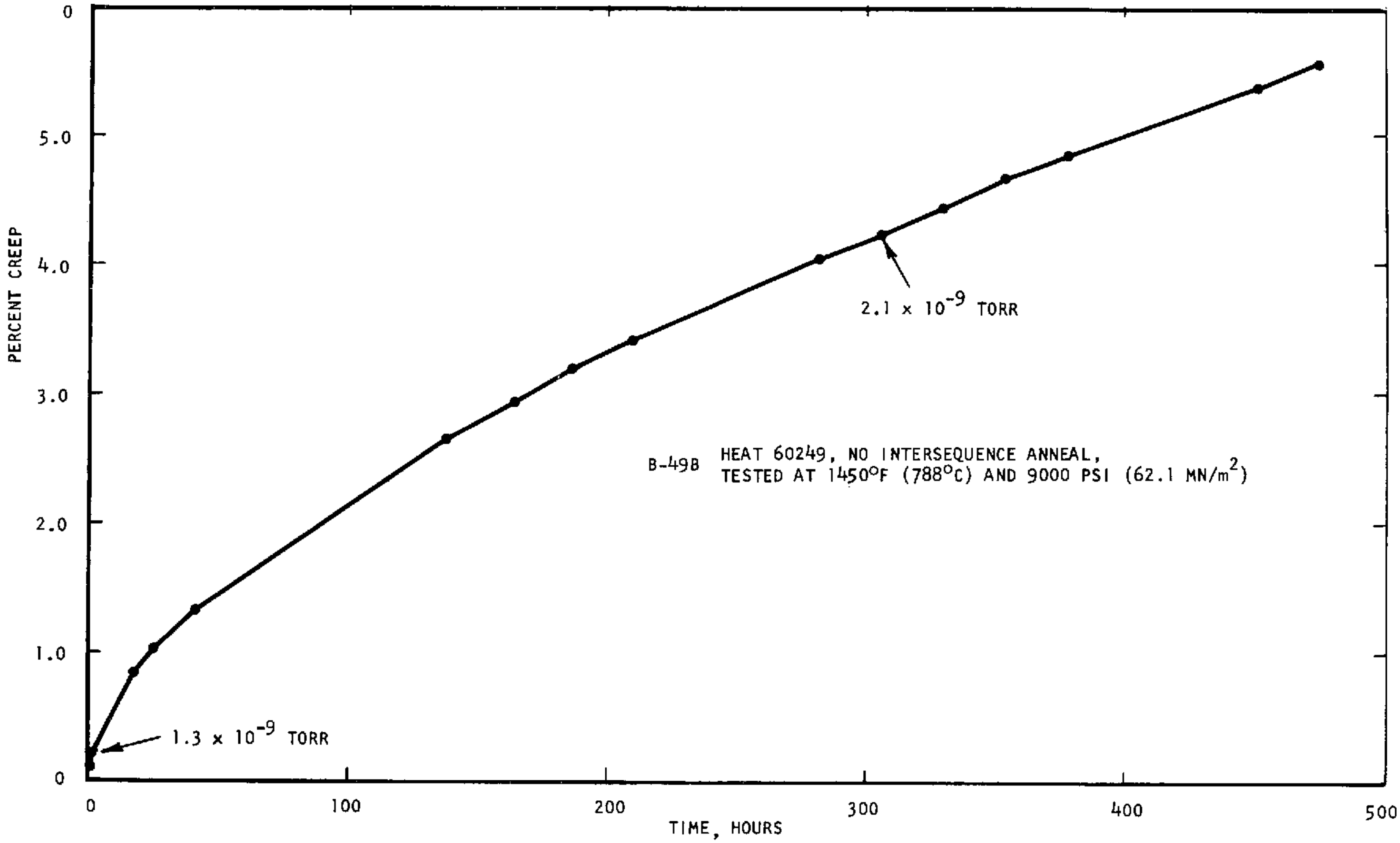

FIGURE III-17. CREEP TEST DATA, PURE TANTALUM, TEST NO. B-49B, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

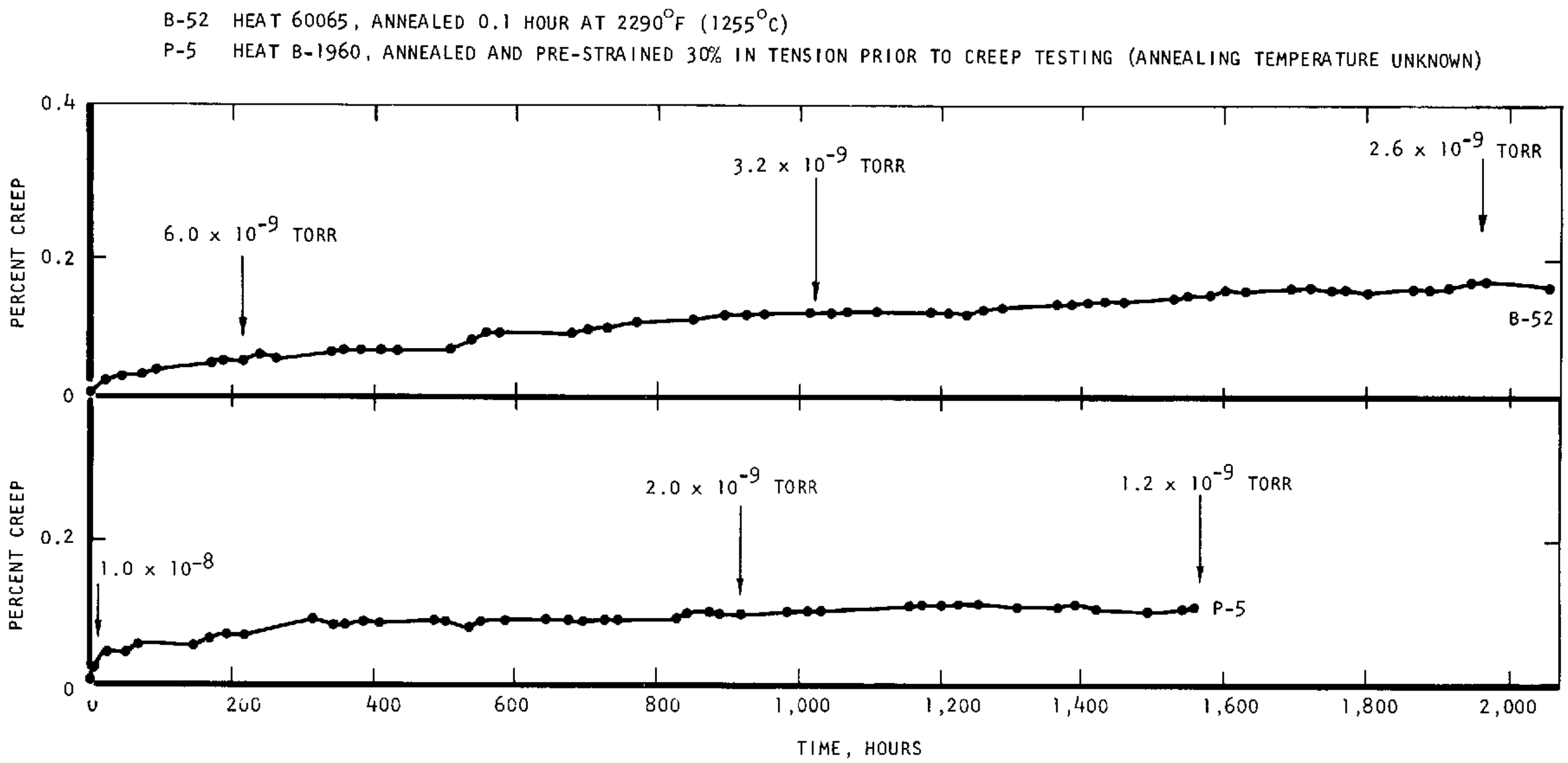

FIGURE III-18. CREEP TEST DATA, PURE TNATALUM, TESTED AT 1350°F (732°C) AND 6.5 KSI (44.8 MN/M^2), TEST NOS. B52 AND P5, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

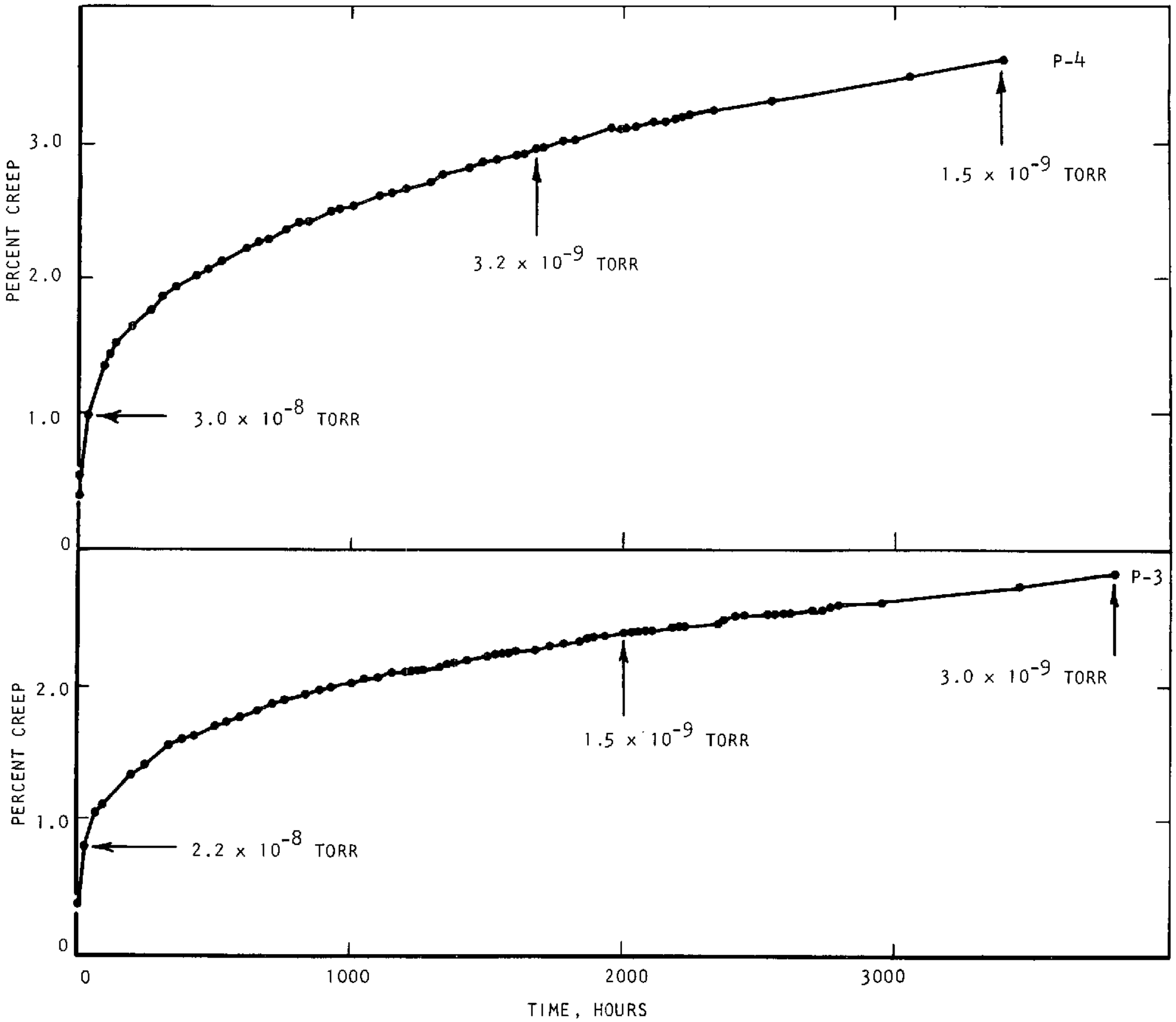

FIGURE III-19 CREEP TEST DATA, PURE TANTALUM HEAT NO. B-1960 ANNEALED (TEMPERATURE UNKNOWN) AND TESTED AT 1350°F (732°C) AND 6.5 KSI (44.8 MN/M^2), TEST NOS. P3 AND P4 (DUPLICATE TESTS, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

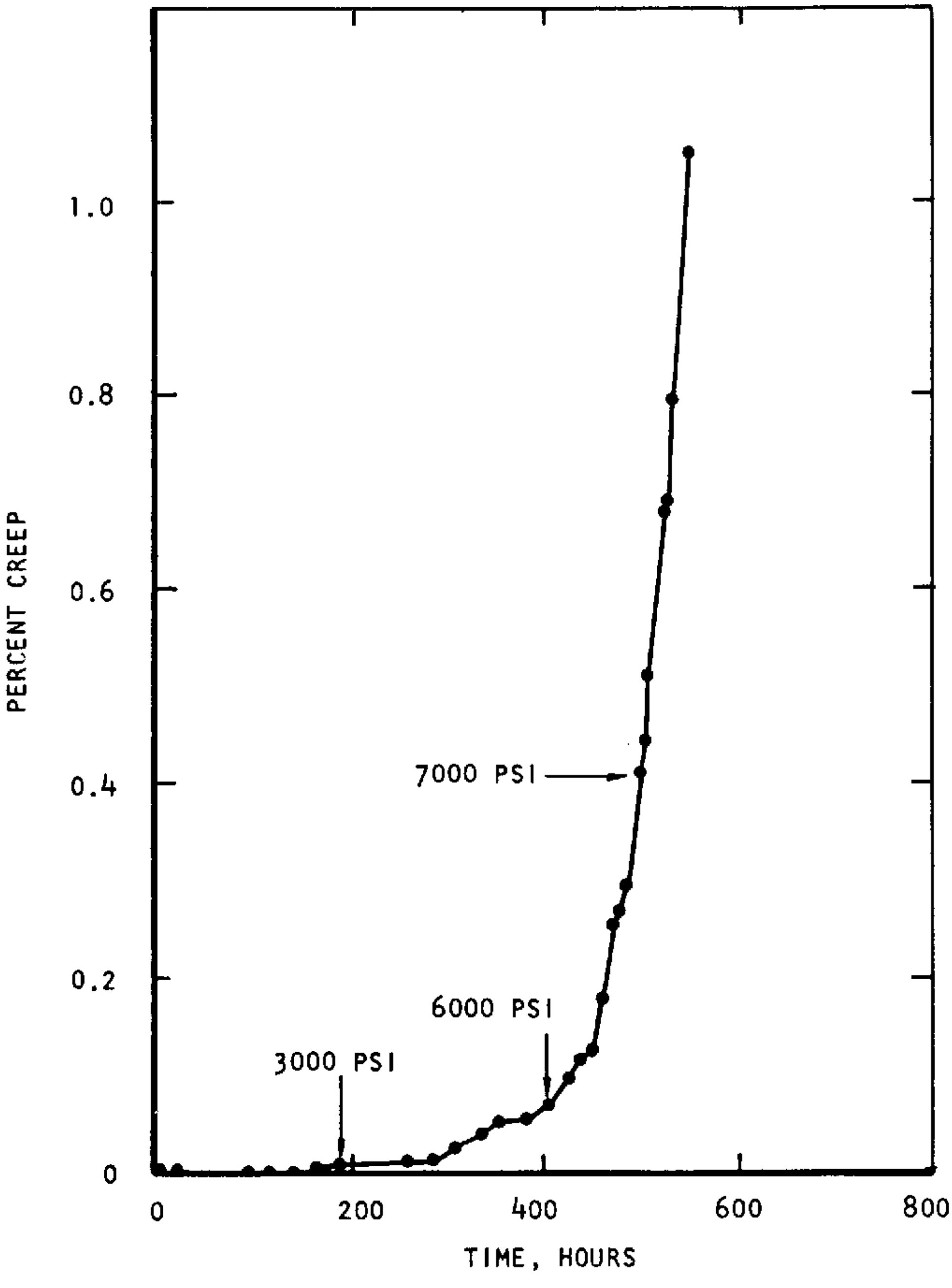

FIGURE III-20. CREEP TEST DATA, PURE Ta HEAT NO. 60249 ANNEALED 0.1 HOUR AT 2290°F (1238°C), TESTED AT 1350°F (720°C) AND 16 PSI/ HOUR, TEST NO. B-47 IN PROGRESSIVE STRESS PROGRAM, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE STRESS AT VARIOUS INTERVALS DURING THE TEST.

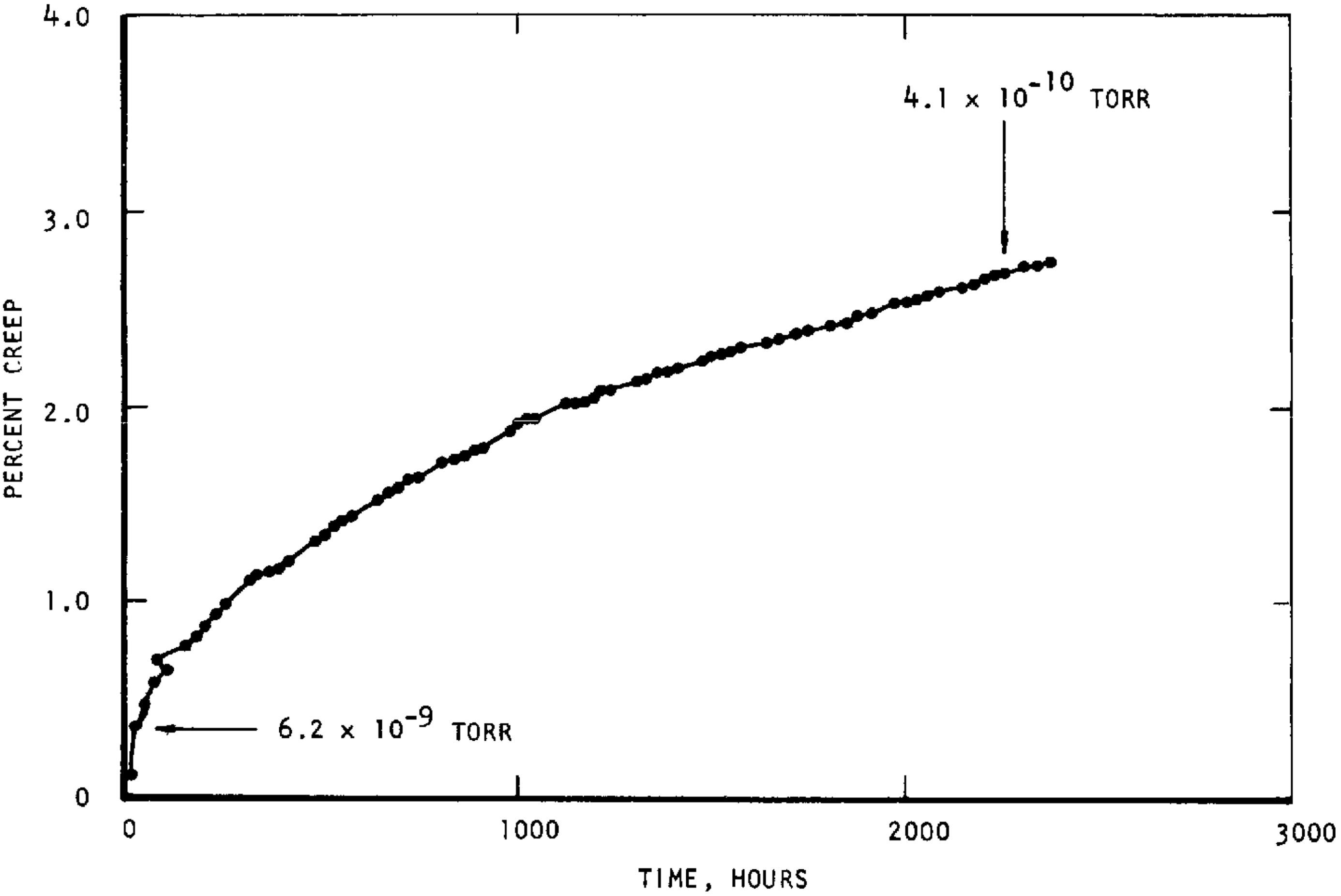

FIGURE III-21. CREEP TEST DATA, PURE Ta HEAT NO. 60249 ANNEALED 1 HOUR AT 2290°F (1258°C), TESTED AT 1450°F (788°C), AND 6.5 KSI (4.48×10^7 N/m^2). TEST NO. B-48A TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

5264 B

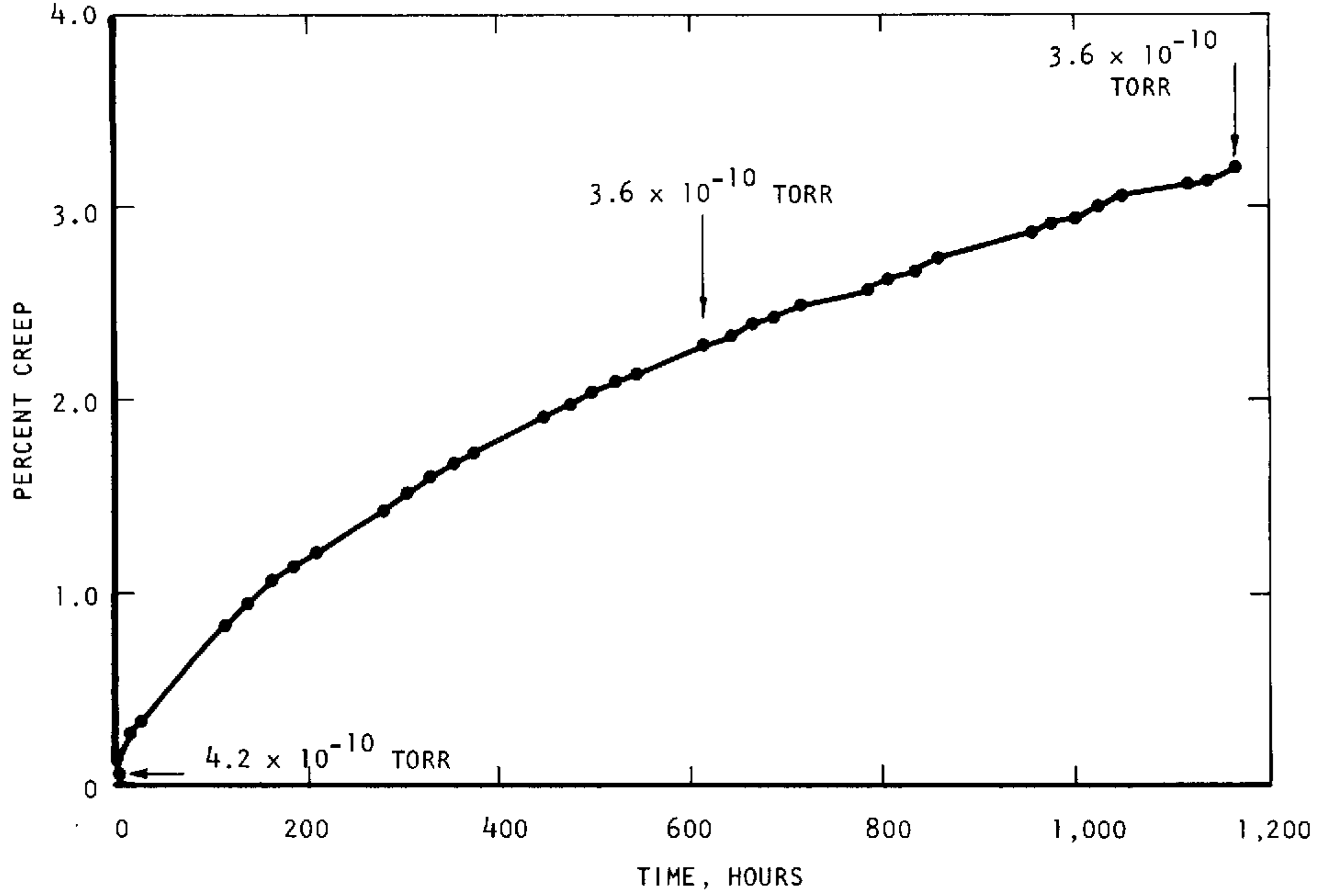

FIGURE III-22. CREEP TEST DATA FOR PURE TANTALUM HAVING A TRANSVERSE BEAD-ON-PLATE WELD, HEAT NO. 60249, TESTED WITH NO INTERSEQUENCE ANNEAL AT 1450°F (788°C) AND 7.5 KSI (52.3 MN/M^2), TEST NO. B48B IN A SEQUENTIAL TEST SERIES, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

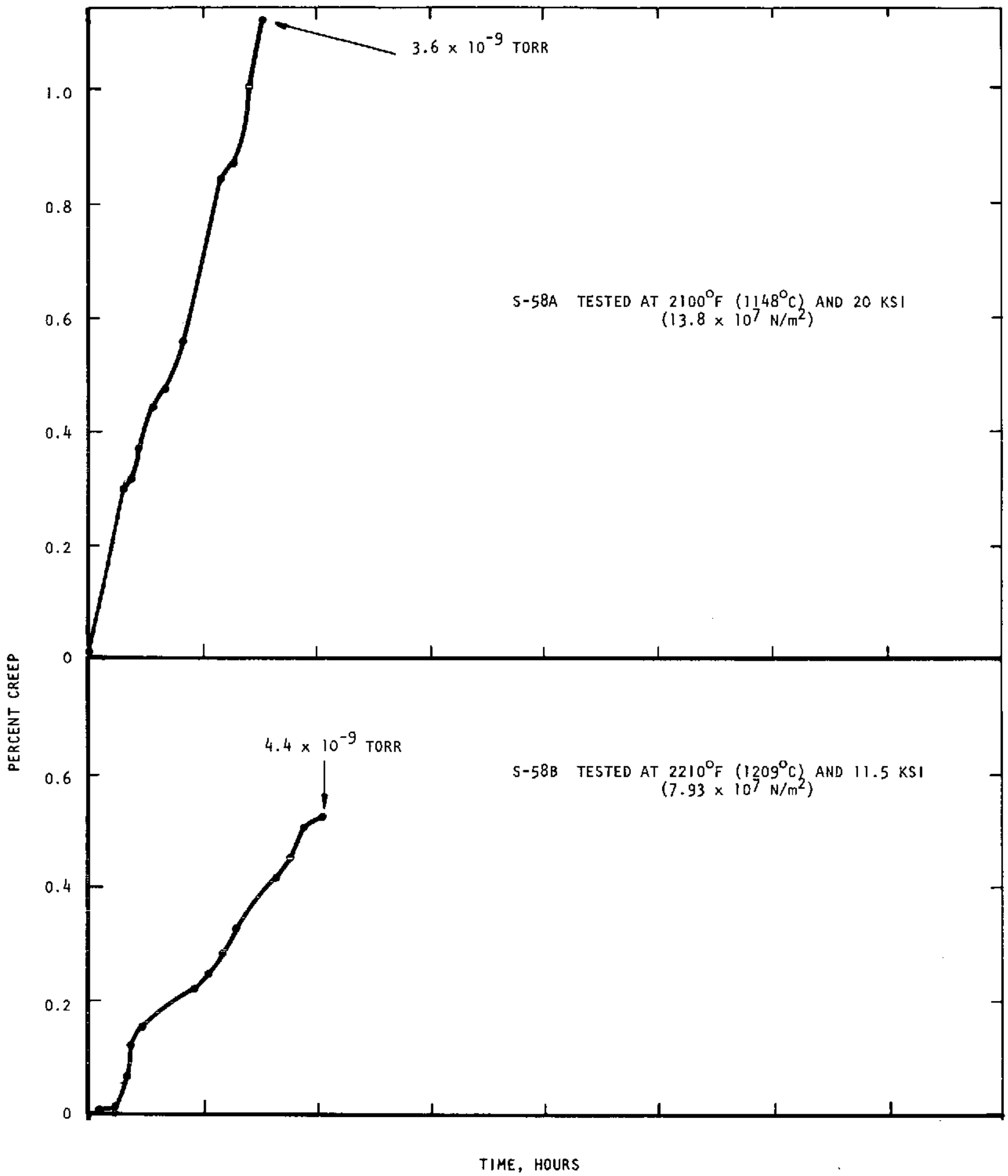

FIGURE III-23. CREEP TEST DATA, Ta-10W HEAT NO. 630003 ANNEALED 1 HOUR AT 3000°F (1649°C) PRIOR TO TESTING AND 1/4 HOUR AT 3000°F (1649°C) BETWEEN EACH SEQUENCE. TEST NOS. S-58A and B, IN A SEQUENTIAL TEST PROGRAM, TESTED IN A VACUUM ENVIRONMENT OF $< 1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

102 C

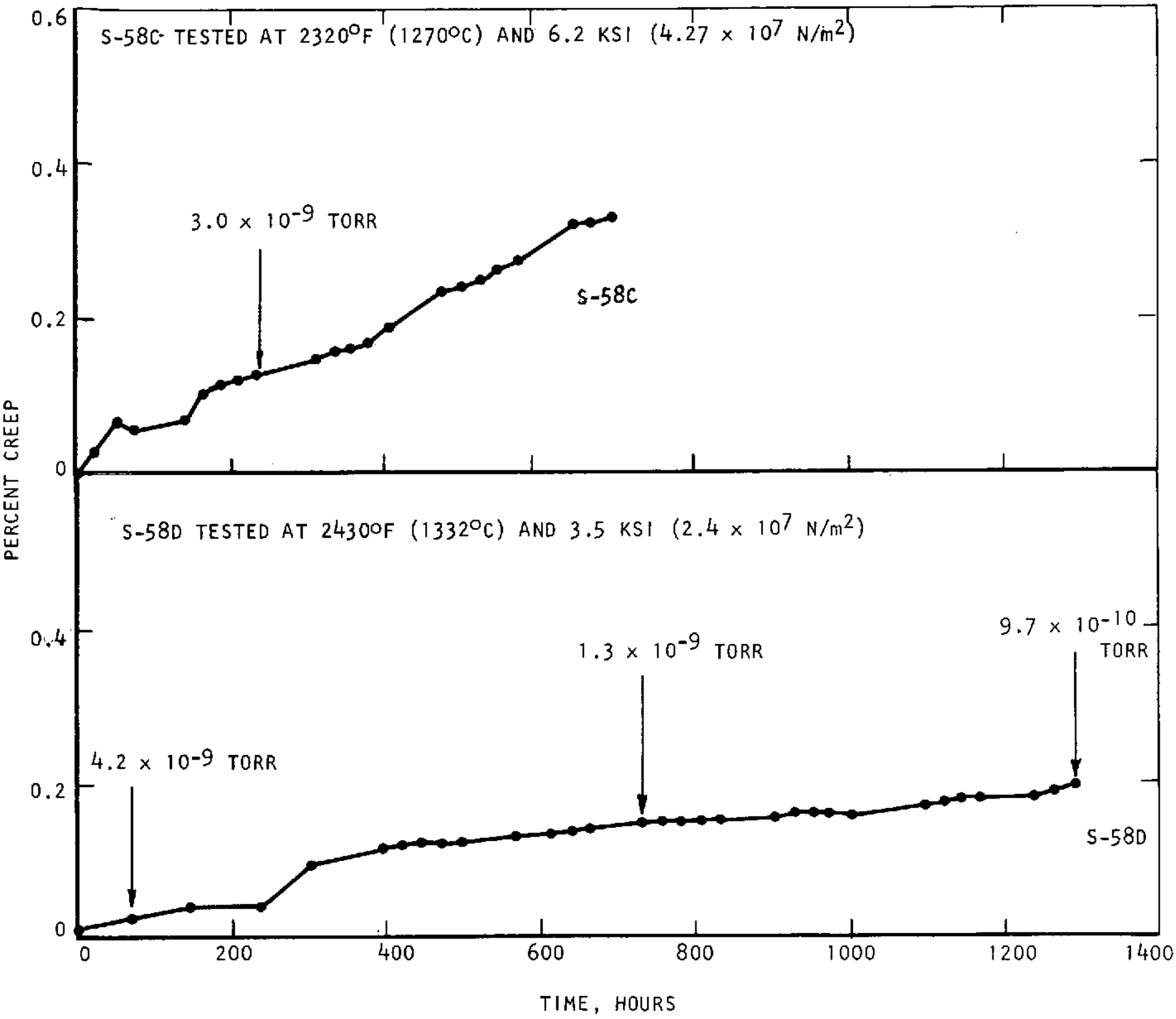

FIGURE III-24. CREEP TEST DATA, TA-10W HEAT NO. 630002 ANNEALED 1/4 HOUR AT 3000°F (1649°C) TEST NOS. S-58C AND S-58D IN A SEQUENTIAL TEST PROGRAM, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

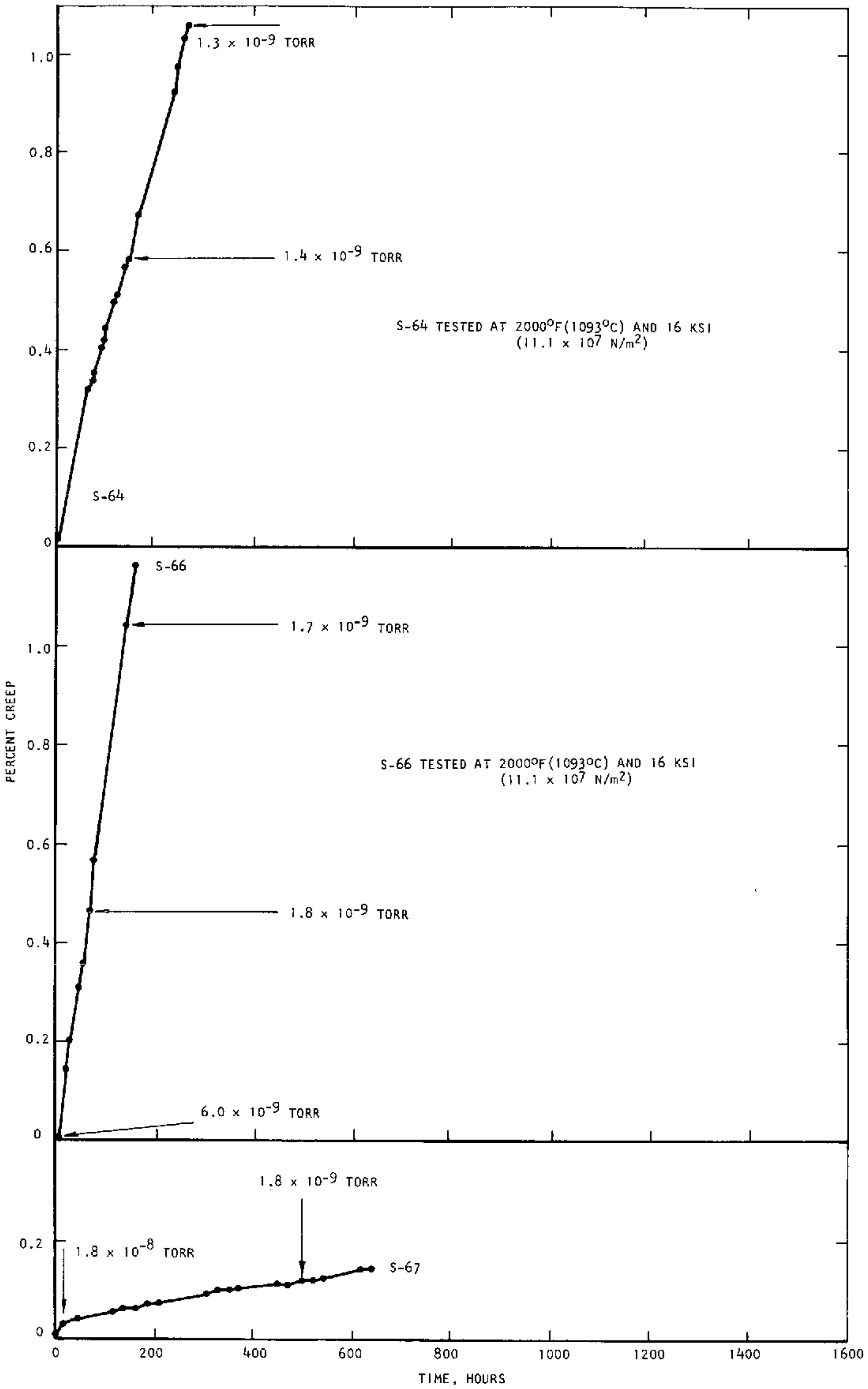

FIGURE III-25. CREEP TEST DATA, Ta-10W HEAT NO. 630002 ANNEALED 1 HOUR AT 3000°F (1649°C), TEST NOS. S-64 AND S-66, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

5268 B

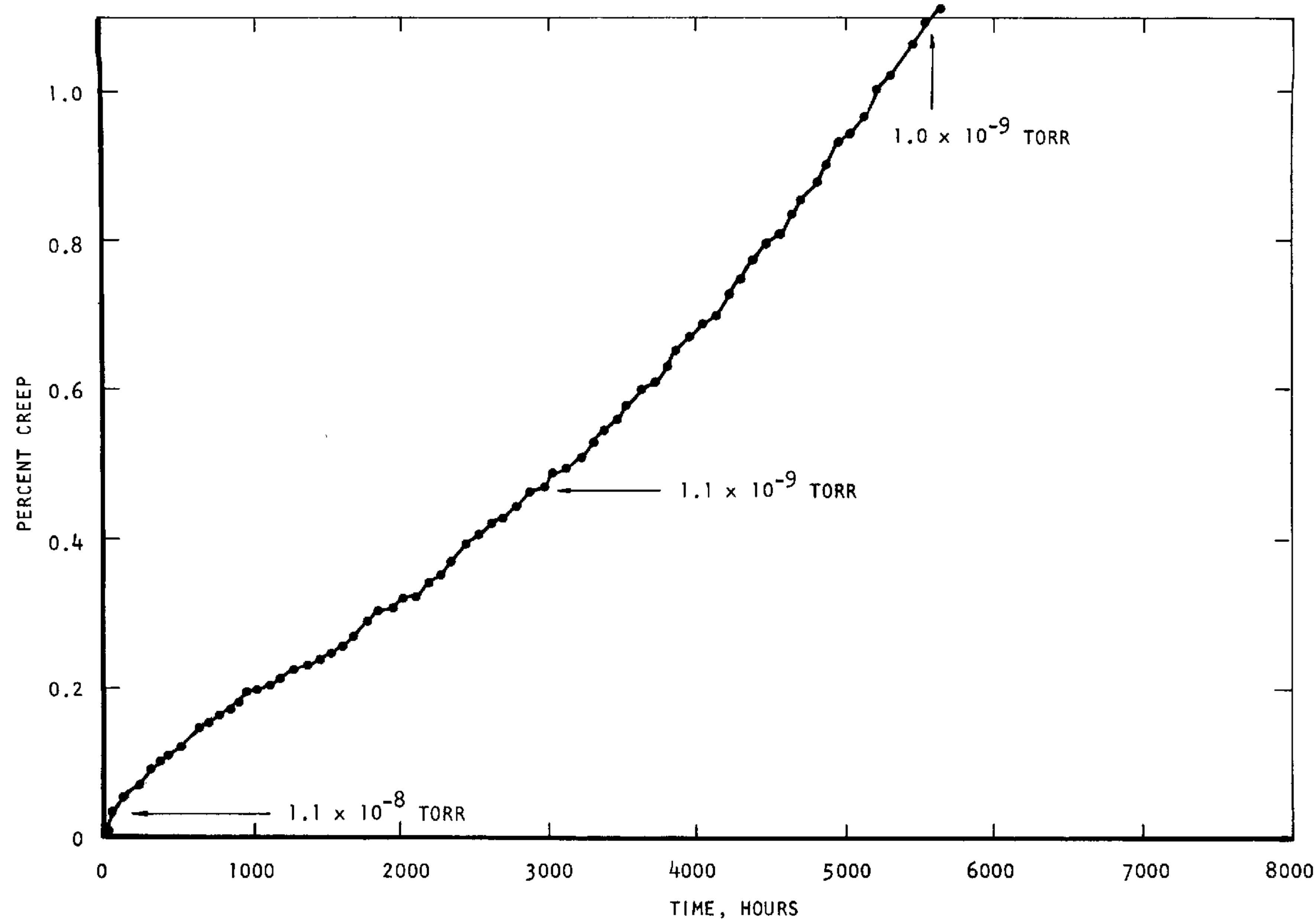

FIGURE III-26. CREEP TEST DATA, Ta-10W HEAT NO. 630002 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED AT 2000°F (1093°C), AND 12 KSI (8.26×10^7 N/m^2), TEST NO. S-67, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR.

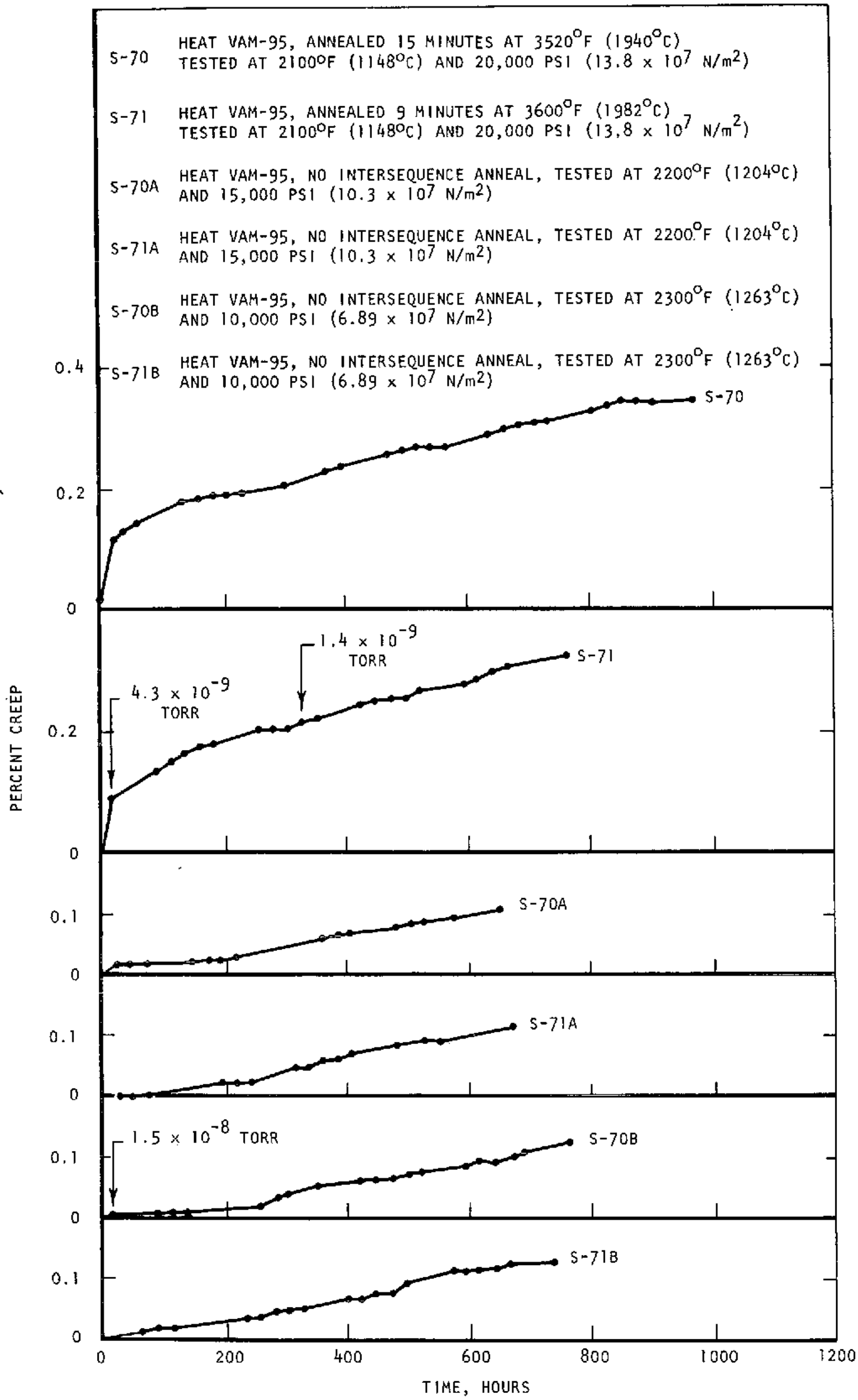

FIGURE III-27. CREEP TEST DATA, ASTAR 811C HEAT NO. VAM-95, TESTS NO. S-70, 70A, 70B, 71, 71A, AND 71B IN SEQUENTIAL TEST PROGRAMS, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

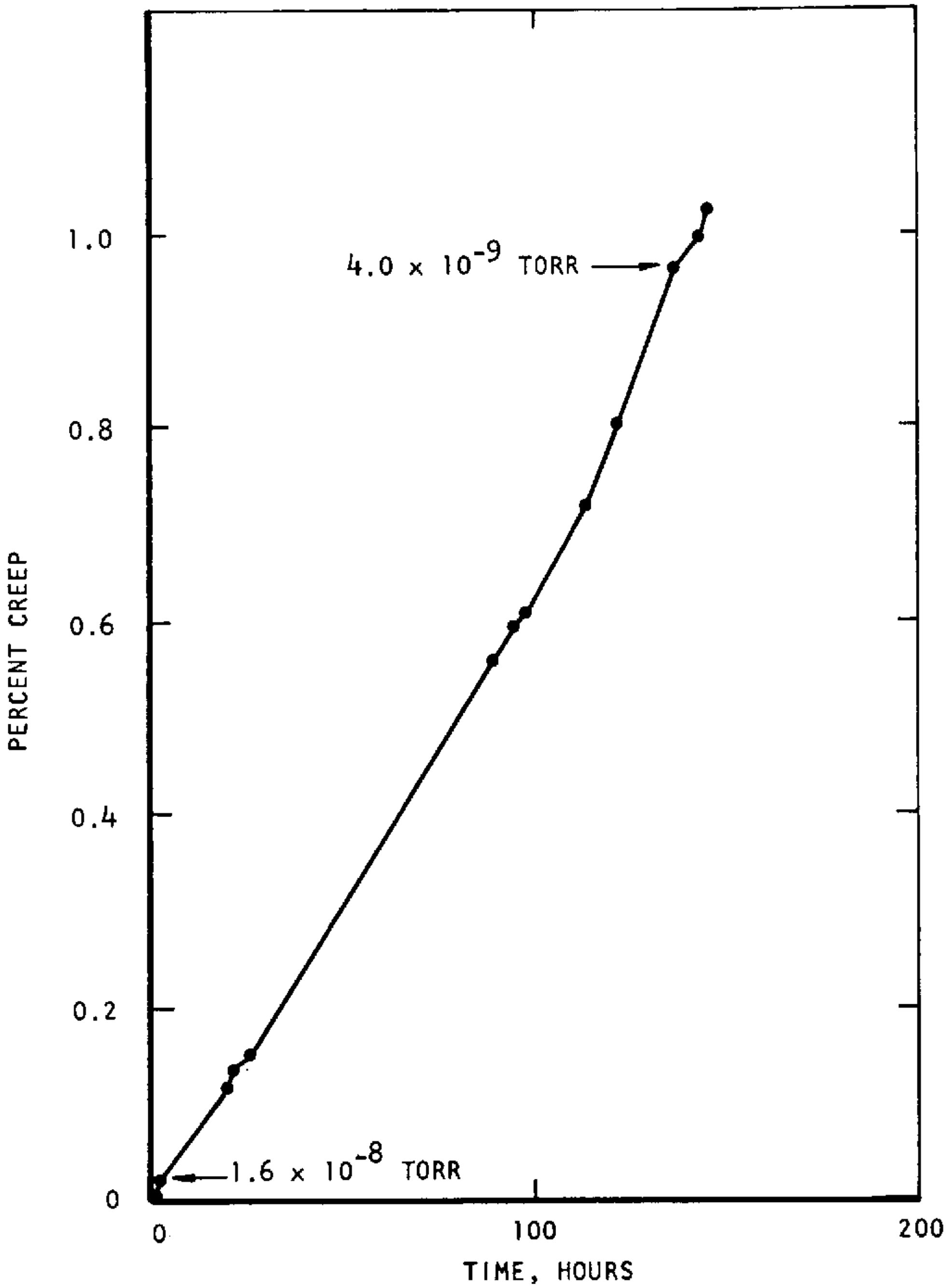

FIGURE III-28. CREEP TEST DATA, ASTAR 811C HEAT NO. VAM-95 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED AT 2400°F (1316°C) AND 15 KSI (10.3×10^7 N/m^2), TEST NO. S-75, TESTED IN A VACUUM ENVIRONMENT OF <1 $\times 10^{-8}$ TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

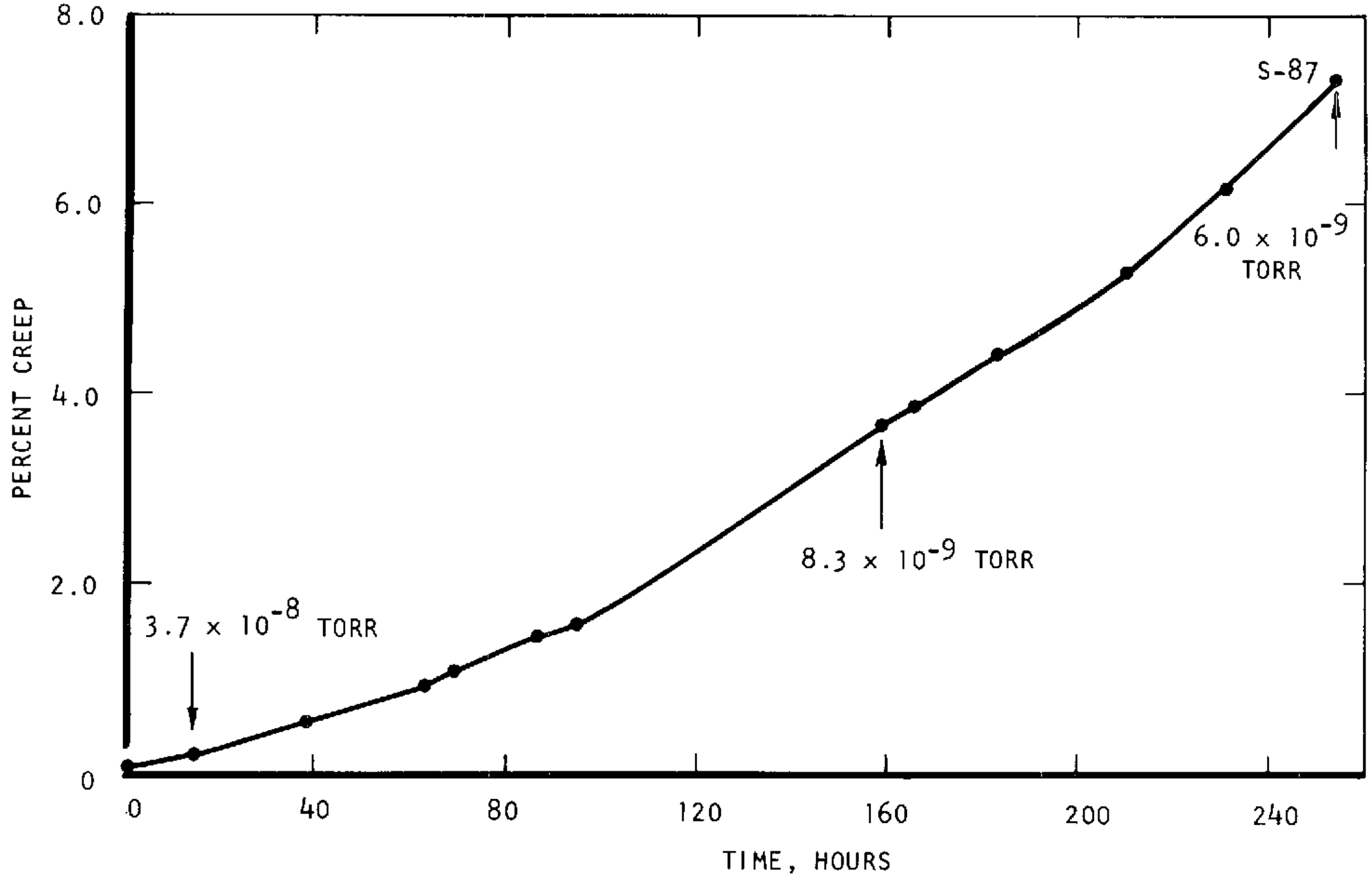

FIGURE III-29. CREEP TEST DATA, ASTAR 811C SPECIMEN NO. R-1 FROM ALKALI METAL EXPOSURE PROGRAM, TESTED IN THE AS-RECEIVED CONDITION AT 2400°F (1316°C) AND 15 KSI (103 MN/M^2), TEST NO. S87, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

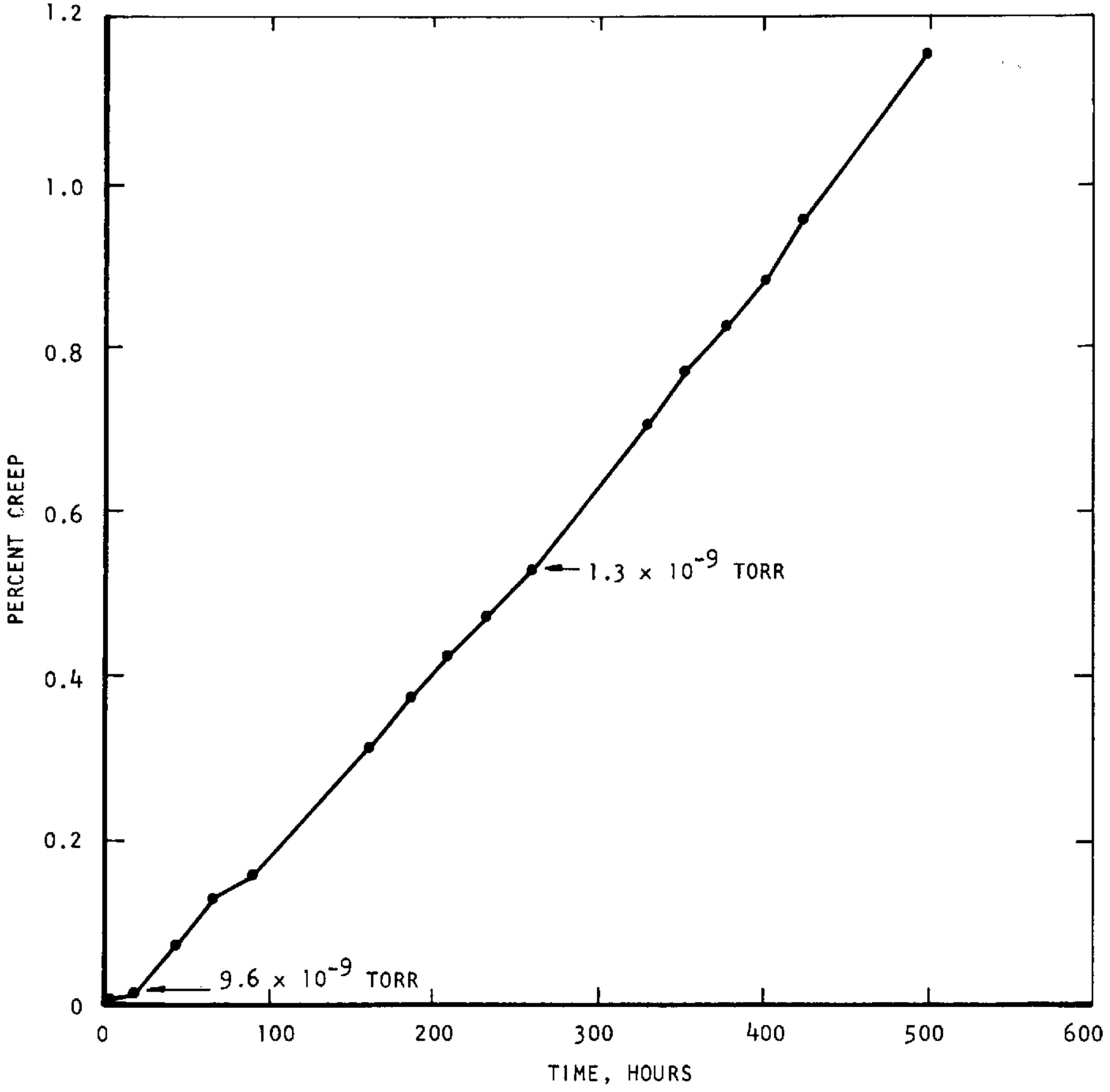

FIGURE III-30. CREEP TEST DATA, ASTAR 811C HEAT NO. VAM-95 ANNEALED 0.33 HOUR AT 3600°F (1982°C), TESTED AT 2400°F (1316°C) AND 15 KSI (10.3×10^7 N/m^2), TEST NO. S-73 TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

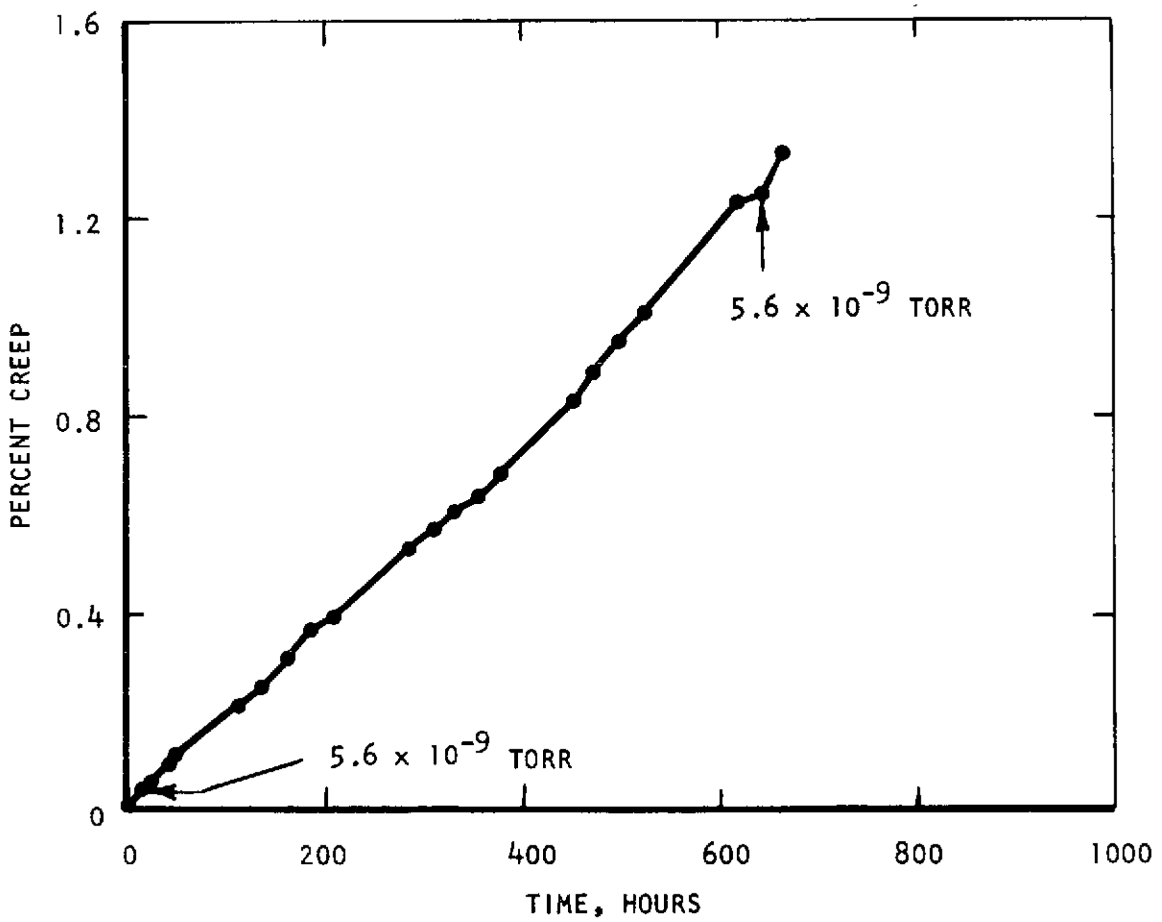

FIGURE III-31. CREEP TEST DATA, ASTAR 811C, HEAT NO. VAM-95 ANNEALED 24 HOURS AT 3270°F (1700°C), TESTED AT 2400°F (1316°C) AND 15 KSI (103 MN/m^2), TEST NO. S-81, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

5731 B

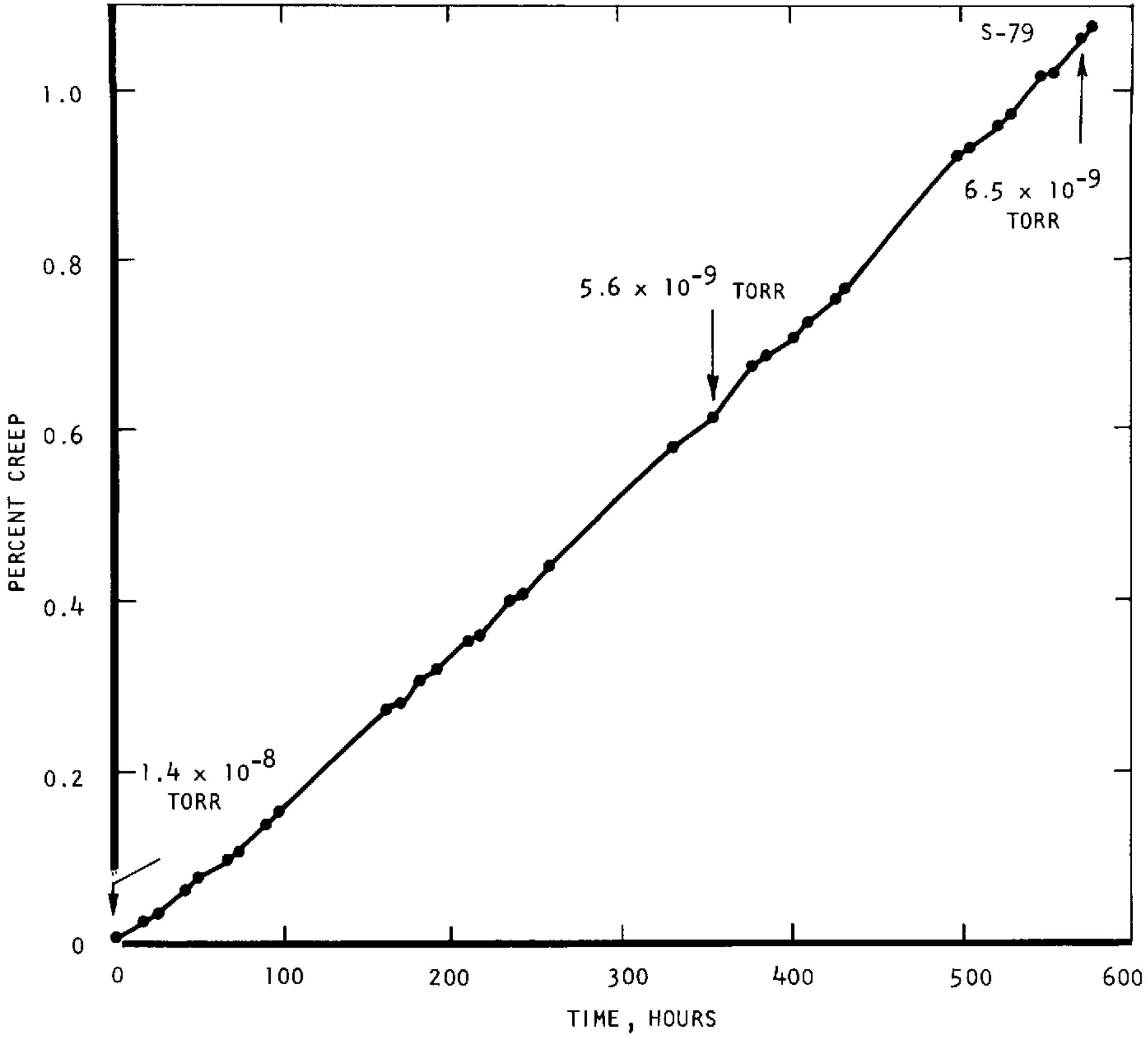

FIGURE III-32. CREEP TEST DATA, ASTAR 811C HEAT NO. VAM 95 ANNEALED 5 HOURS AT 3450°F (1800°C), TESTED AT 2400°F (1316°C) AND 15 KSI (103 MN/M^2), TEST NO. S-79, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

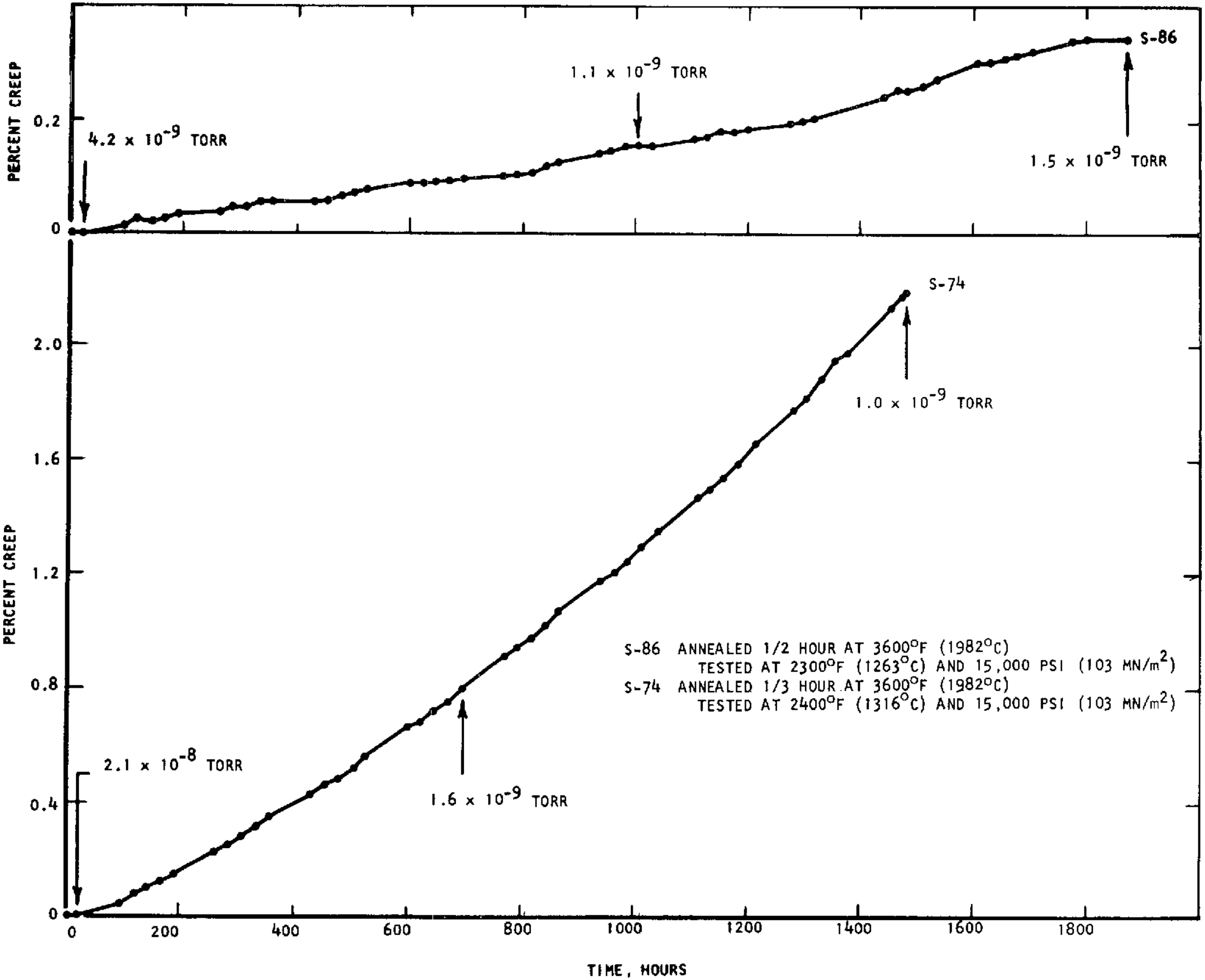

FIGURE III-33 CREEP TEST DATA, ASTAR 811C HEAT NO. 66-650056 TEST NOS. S 74 AND S 86, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

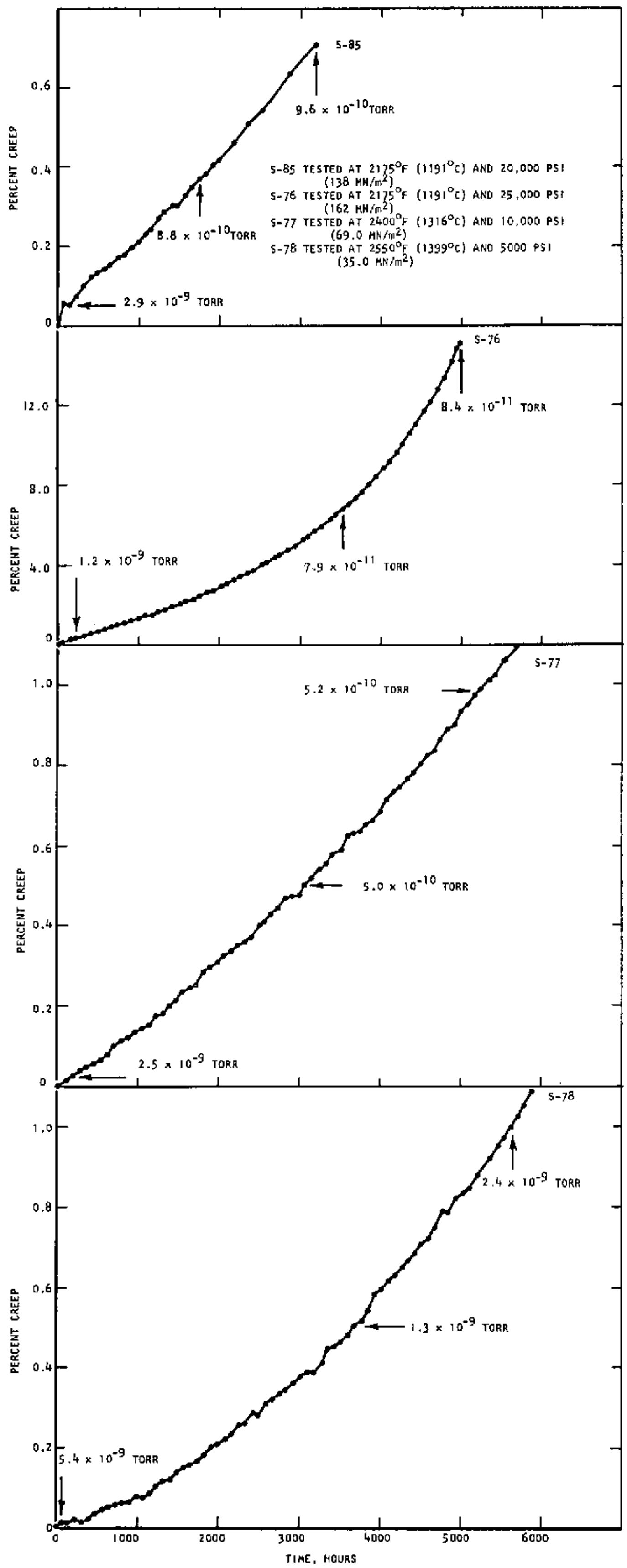

FIGURE III-34. CREEP TEST DATA, ASTAR 811C HEAT NO. 66-650056 ANNEALED 1/2 HOUR AT 3600°F (1982°C), TEST NOS. S85, S76, S77 AND S78, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

125 C

5267 B

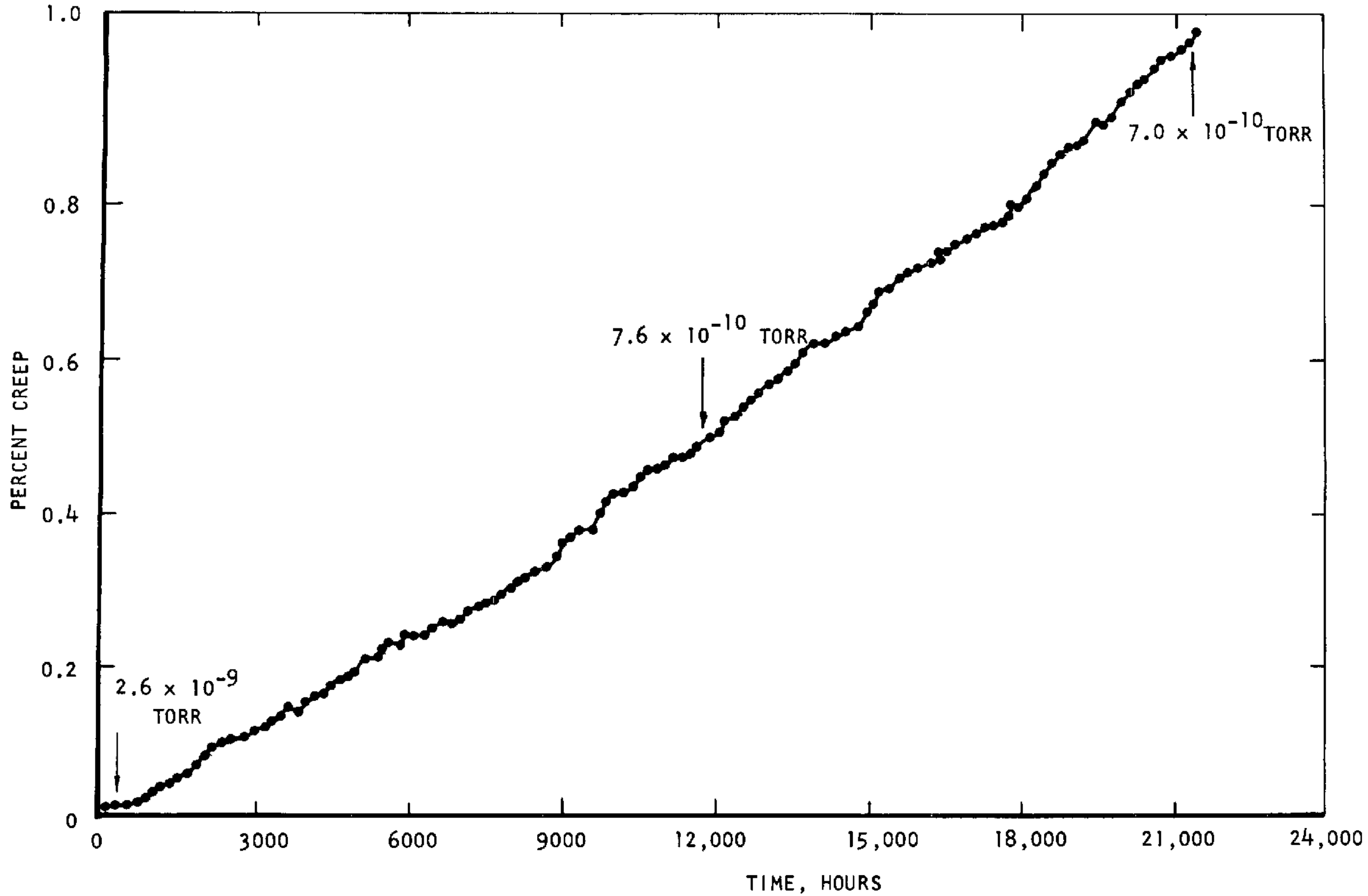

FIGURE III-35. CREEP TEST DATA, ASTAR 811C HEAT NO. NASV-20-WS ANNEALED 0.5 HOUR AT 3600°F (1982°C), TESTED AT 2600°F (1427°C), AND 2 KSI (1.38×10^7 N/m^2), TEST NO. S-29, TESTED IN A VACUUM ENVIRONMENT OF <1×10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

97

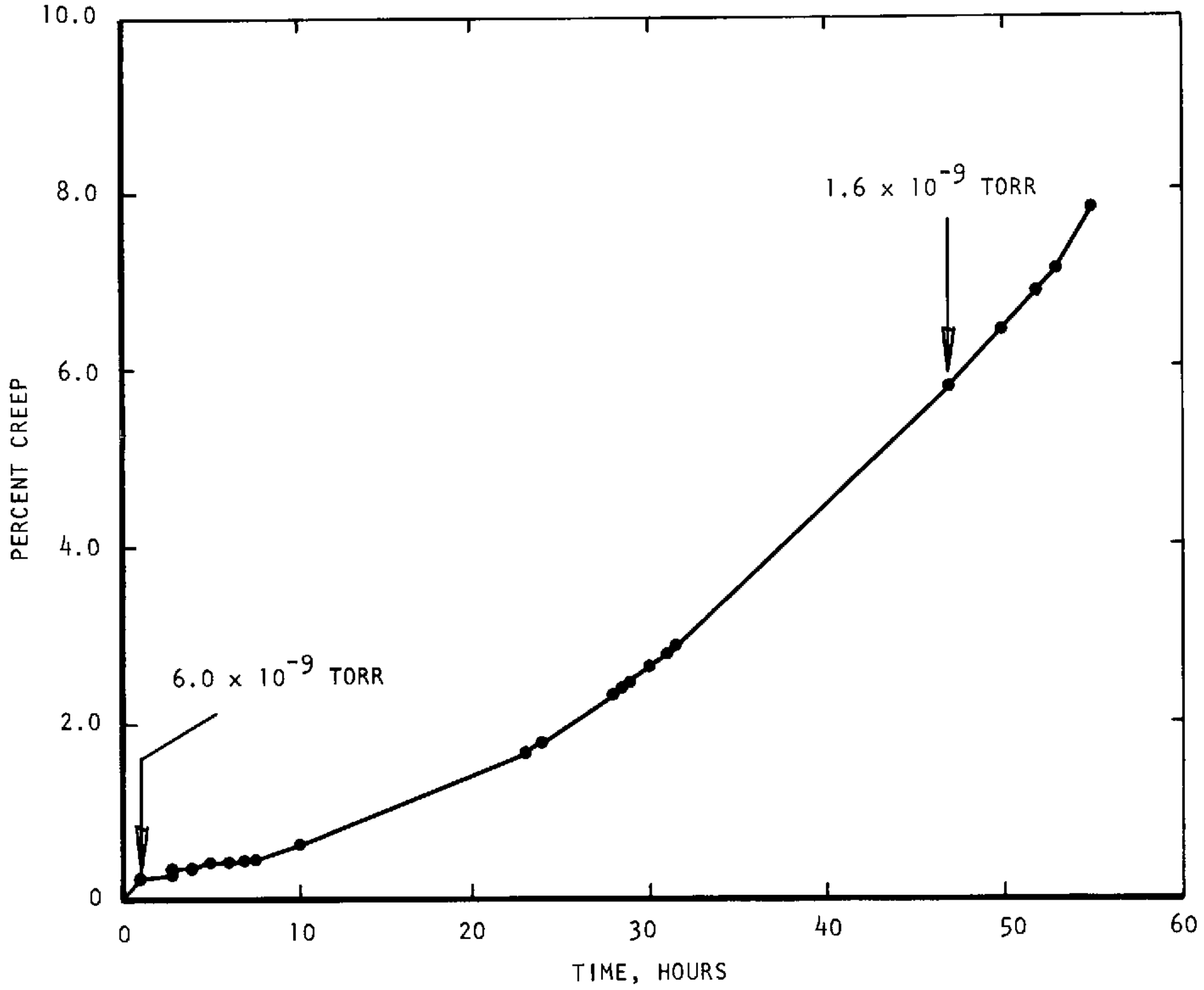

FIGURE III-36. CREEP TEST DATA, T-111 HEAT NO. 650038 ANNEALED 1 HOUR AT 2000°F (1649°C) TESTED AT 2000°F (1093°C) AND 35 KSI (24.1×10^7 N/m^2), TEST NO. B-44, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

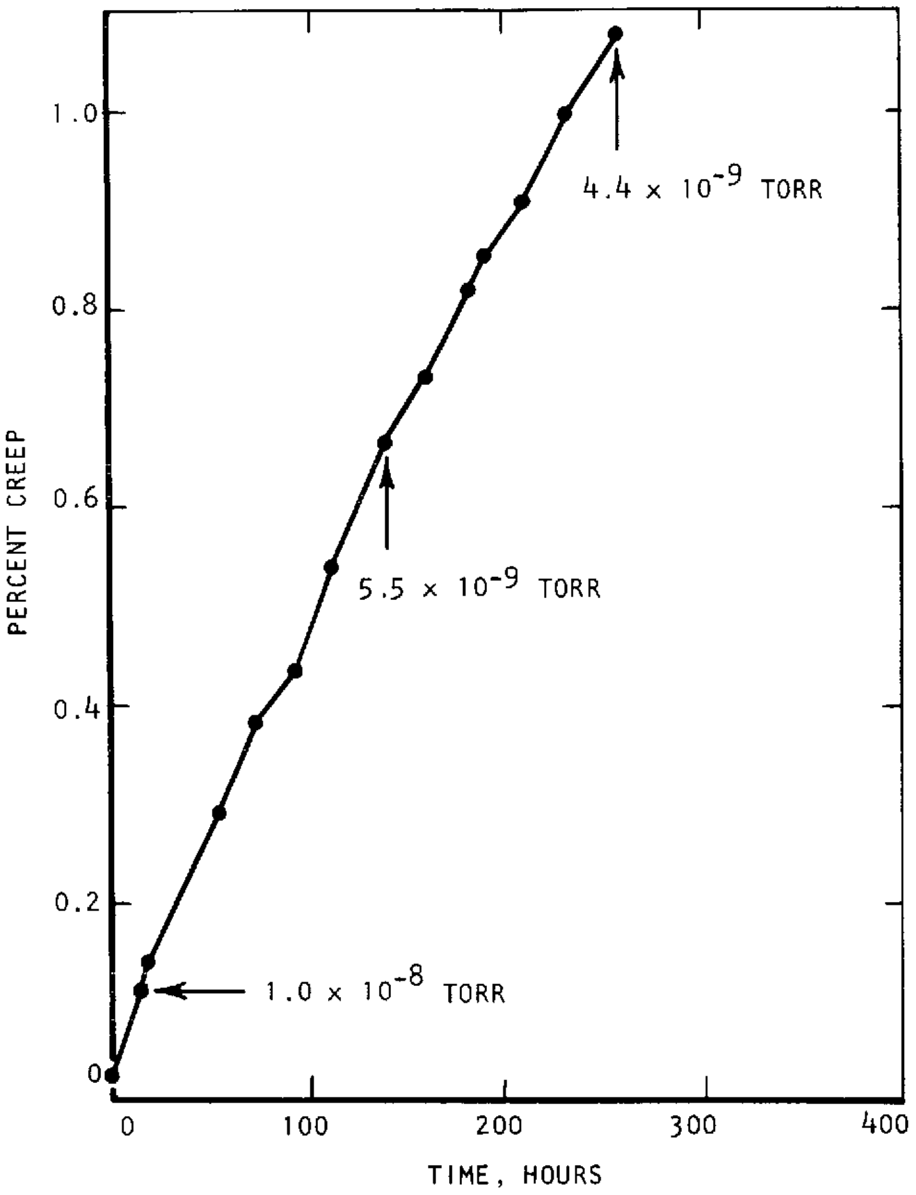

FIGURE III-37. CREEP TEST DATA, T-111 HEAT NO. 65080 ANNEALED 15 HOURS AT 3000°F (1649°C), TESTED AT 2200°F (1204°C) AND 8 KSI (55.1 MN/M^2), TEST NO. S-41, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

129 C

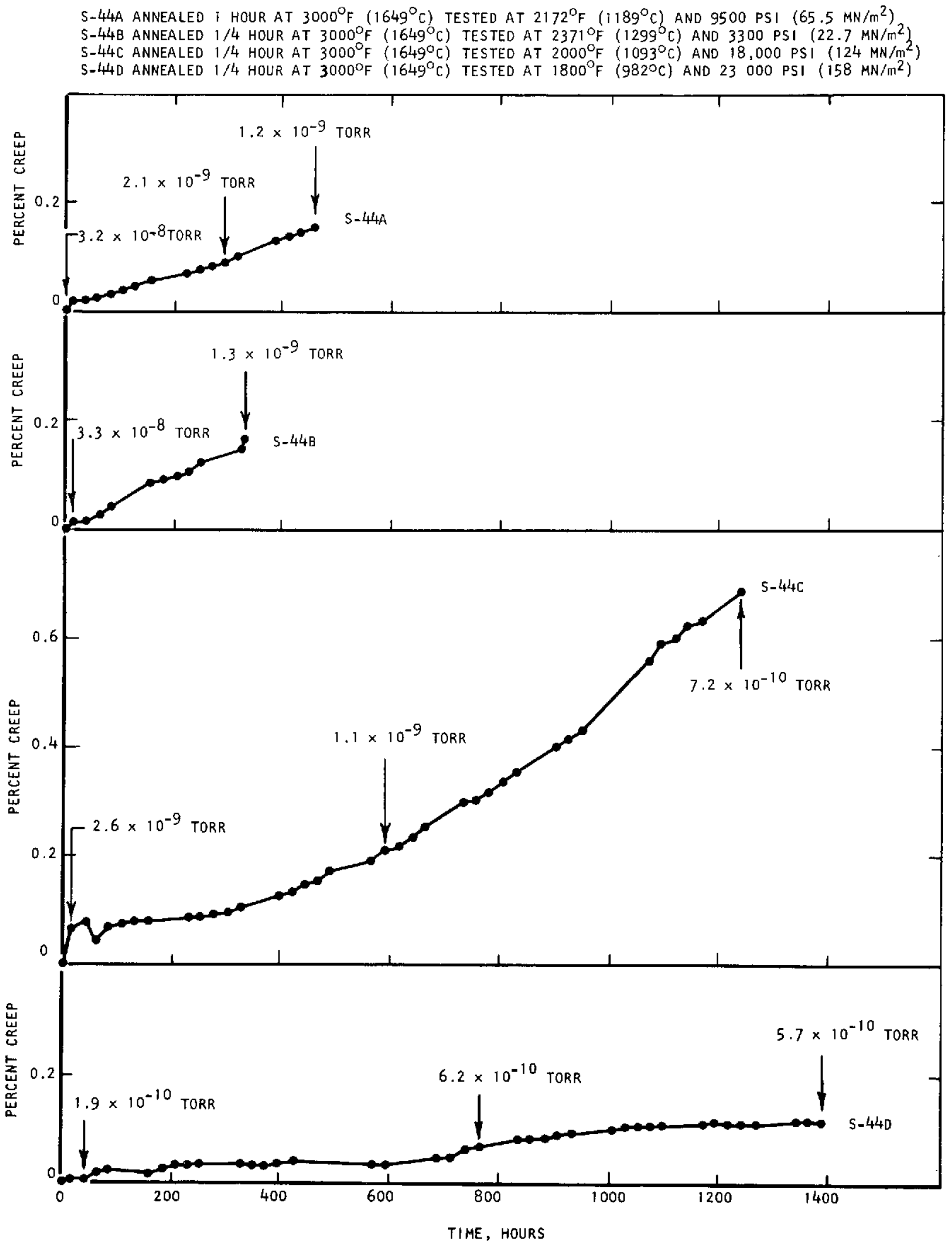

FIGURE III-38. CREEP TEST DATA, T-111 HEAT NO. 65079 TEST NOS. S44A, B, C, AND D IN A SEQUENTIAL TEST SERIES, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

130 c

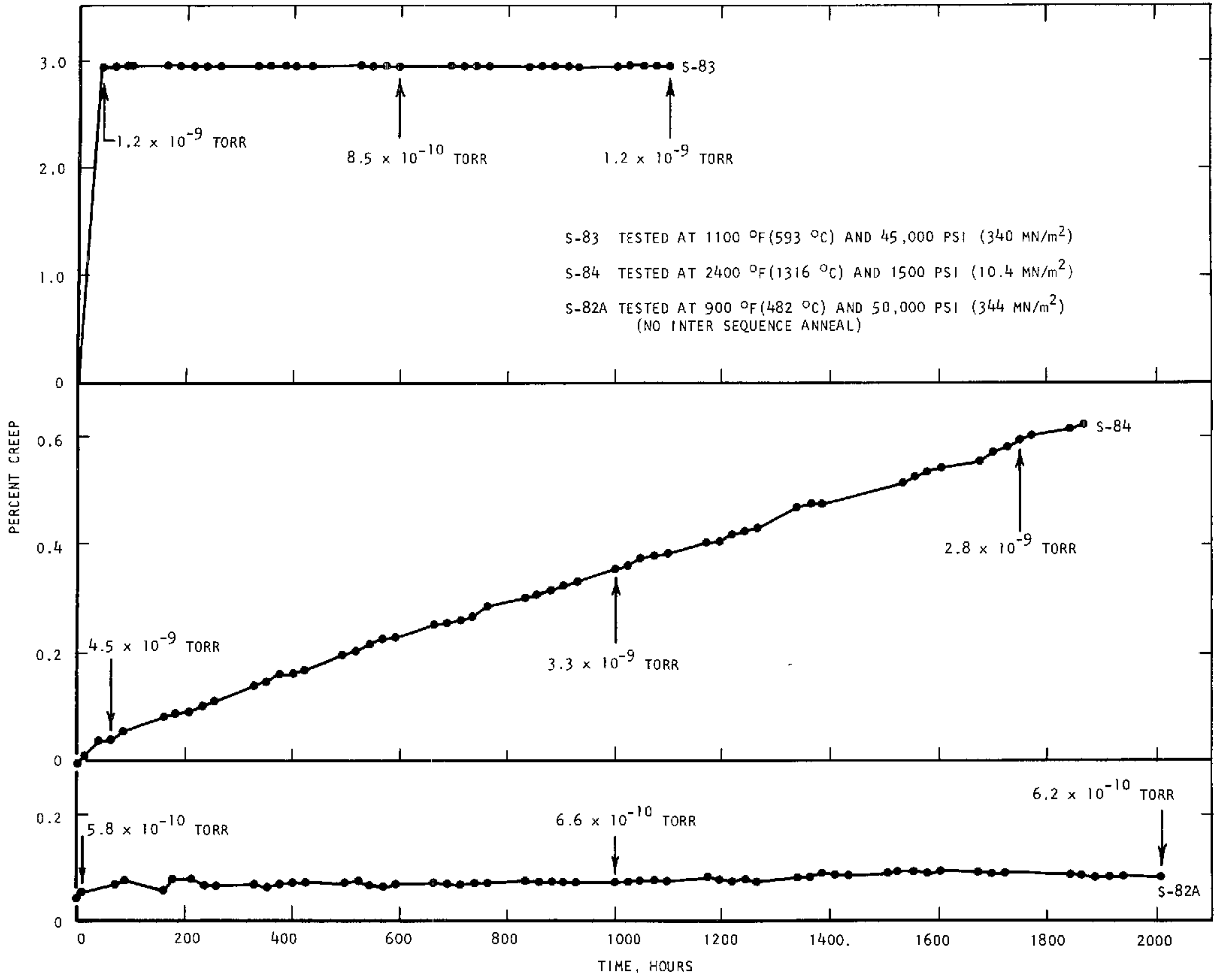

FIGURE III-39. CREEP TEST DATA, T-111 HEAT NO. 650028 ANNEALED 1 HOUR AT 3000°F (1649°C), TEST NOS. S83, S84 AND S82A, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

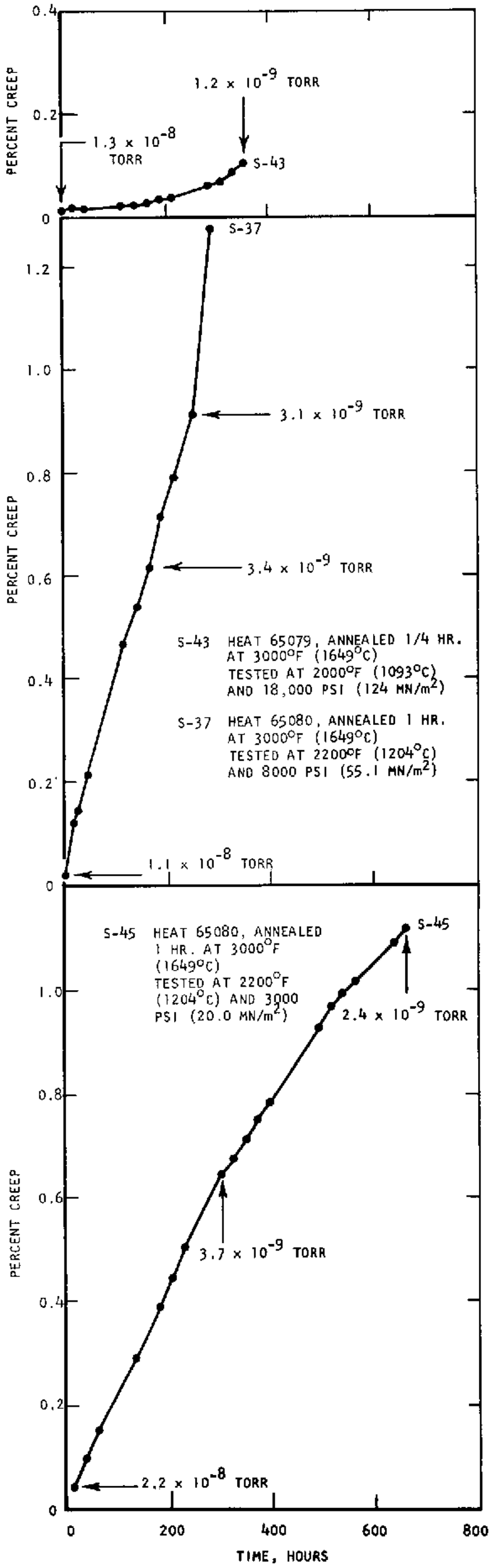

FIGURE III-40. CREEP TEST DATA, T-111, TEST NOS S43, S37 AND S45, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

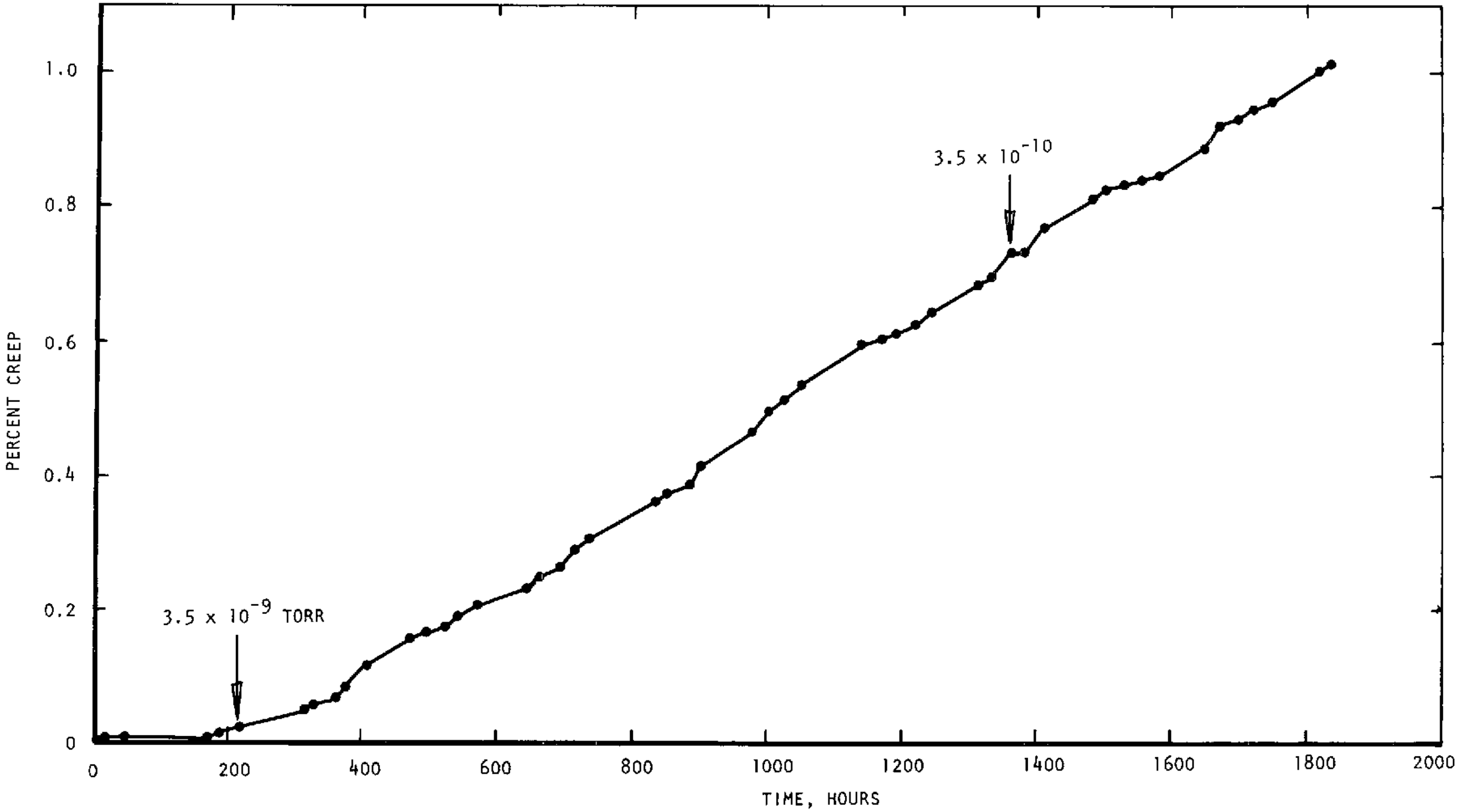

FIGURE III-41. CREEP TEST DATA, T-111 HEAT NO. 650038 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED AT 2000°F (1093°C) AND 20 KSI (13.8×10^7 N/m^2), TEST NO. B-43, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

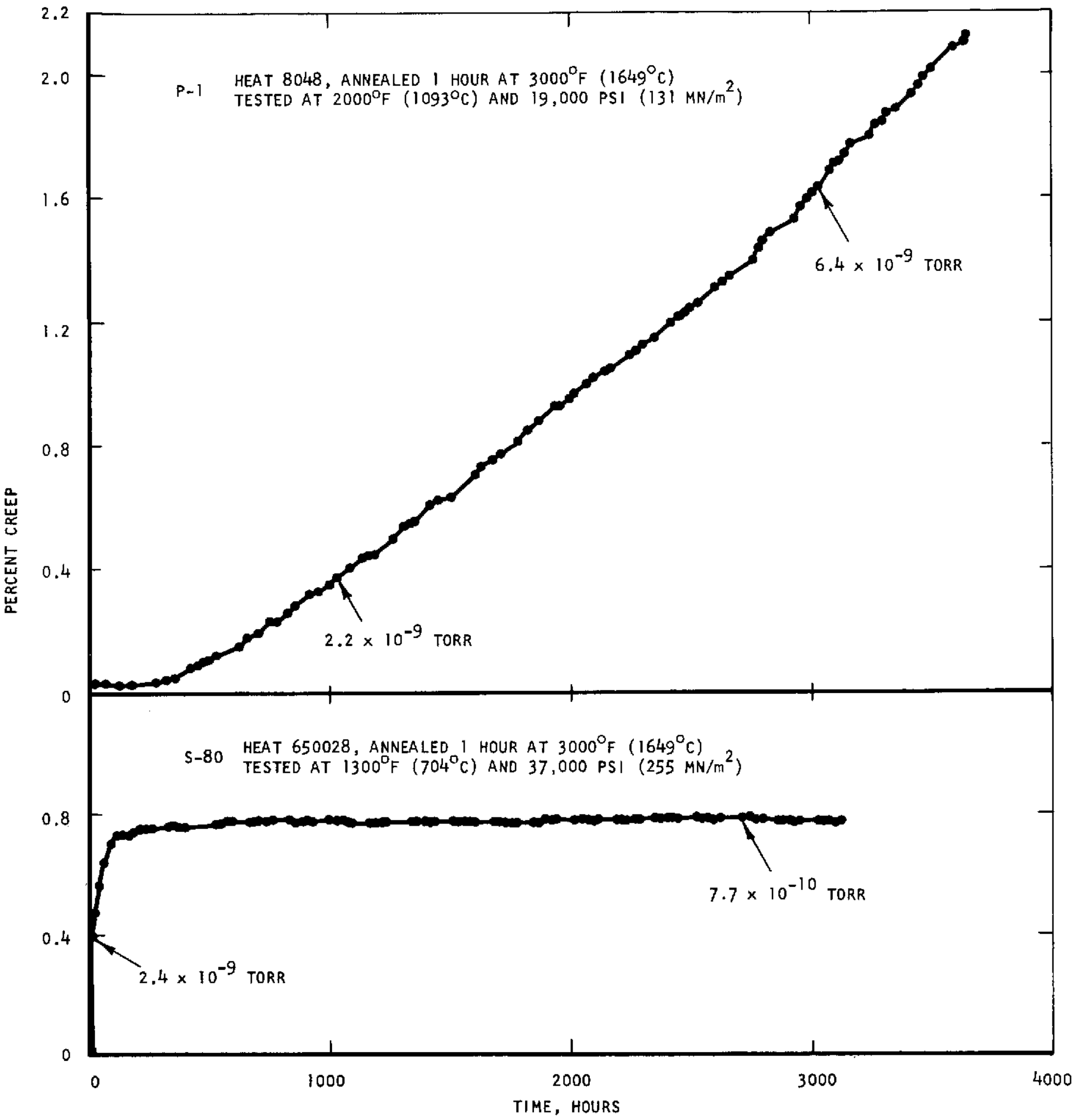

FIGURE III-42. CREEP TEST DATA, T-111, TEST NOS. P-1 AND S-80, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

5729 B

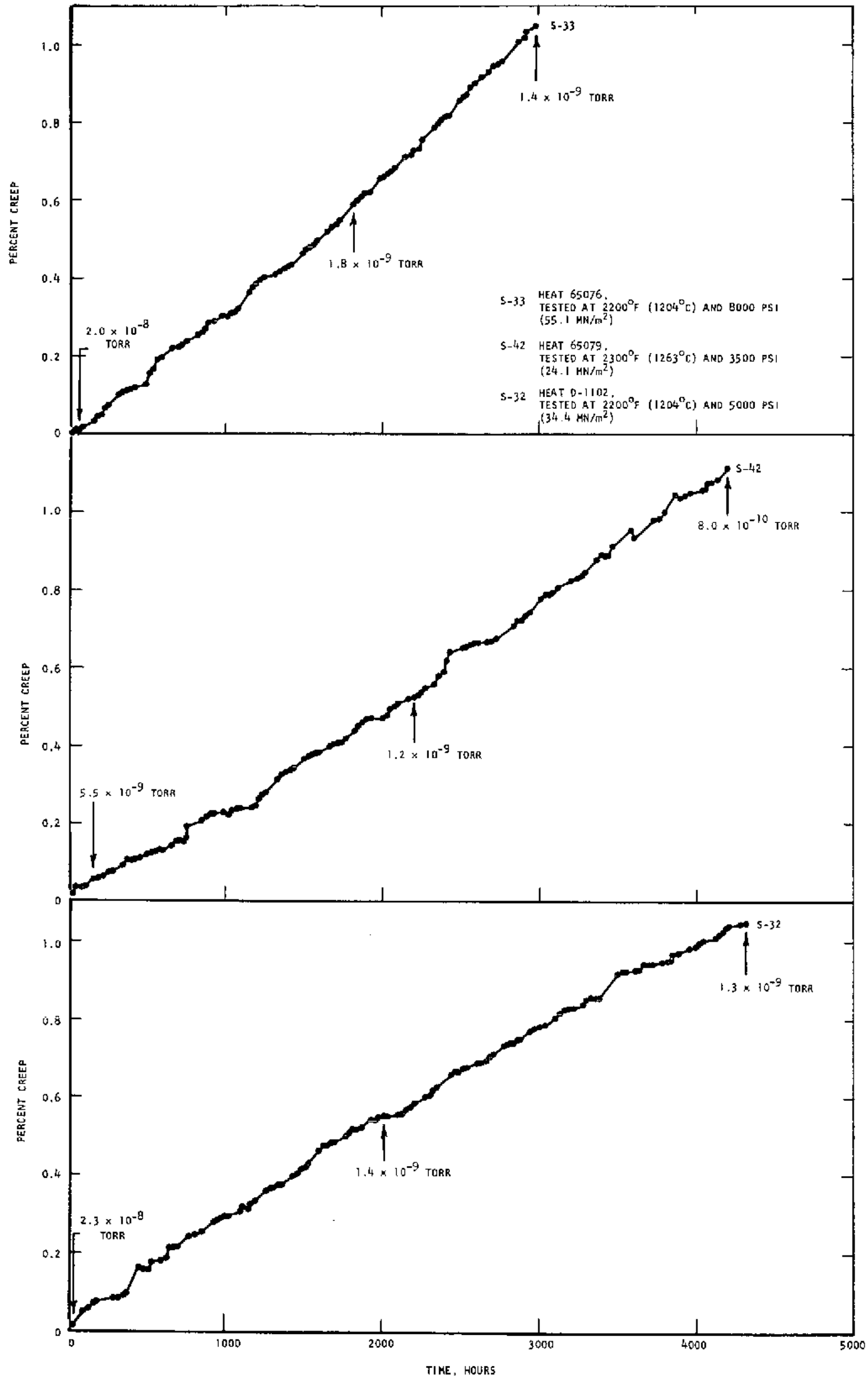

FIGURE III-43. CREEP TEST DATA, T-111 ANNEALED 1 HOUR AT 3000°F (1649°C), TEST NOS. S33, S42 AND S32, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

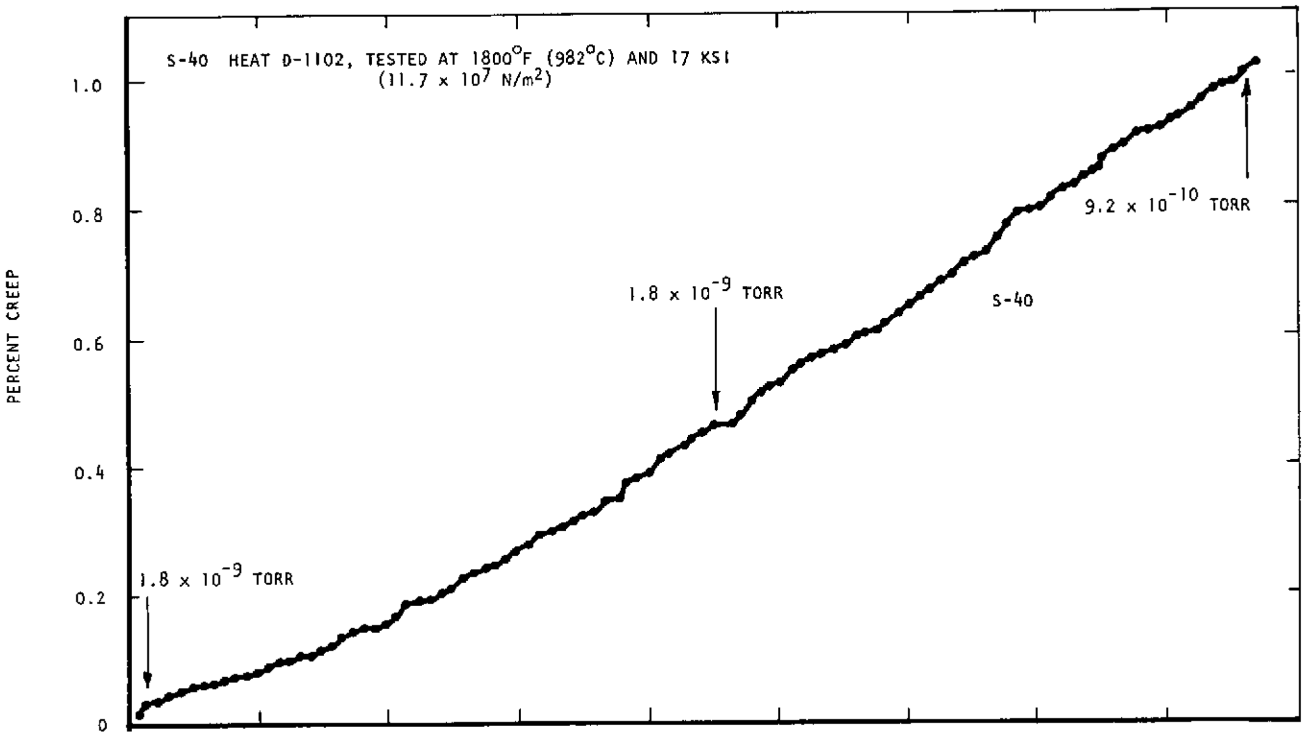

FIGURE III-44. CREEP TEST DATA, T-111 ANNEALED 1 HOUR AT 3000°F (1649°C). TEST NO. S-40, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

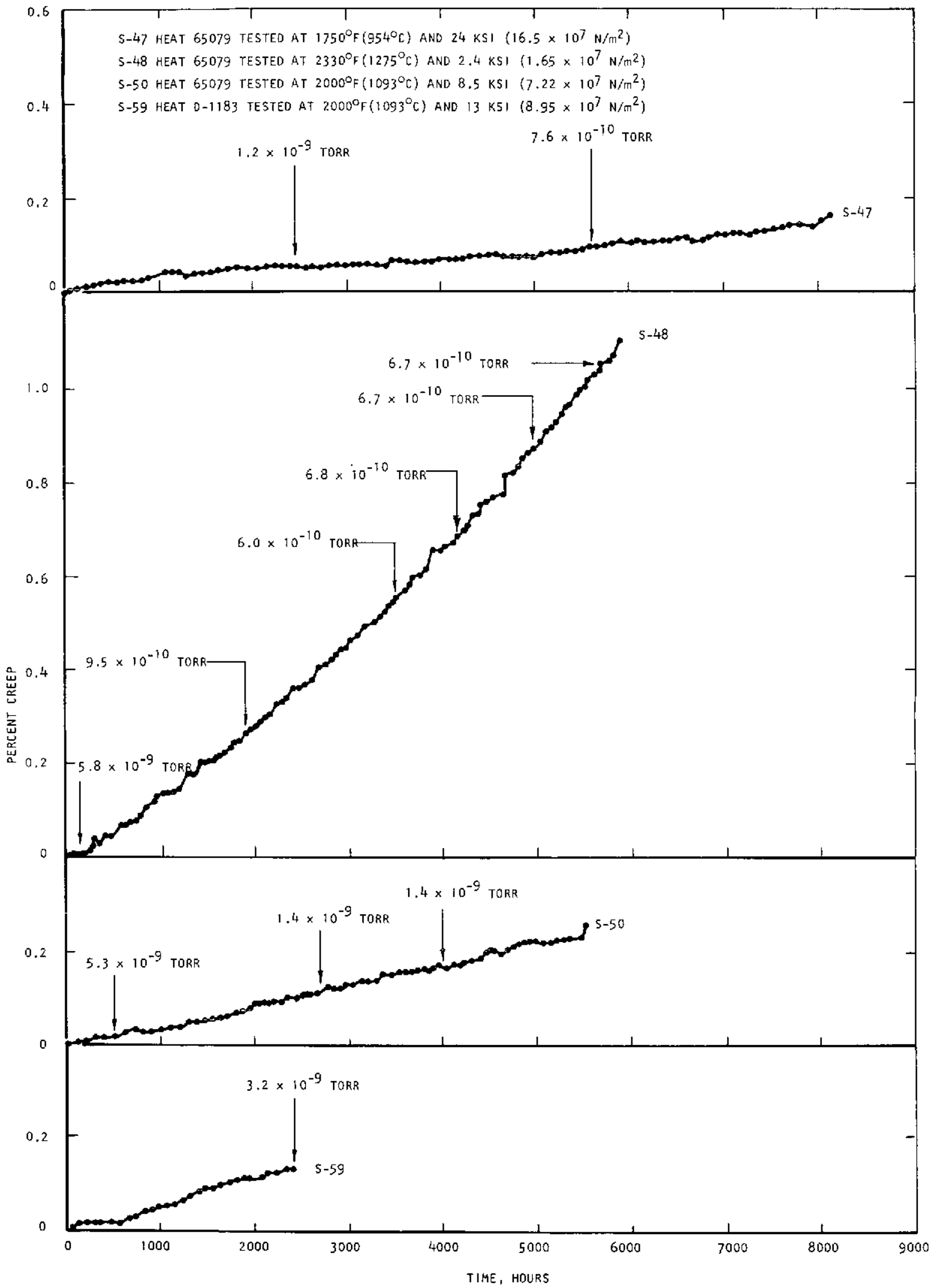

FIGURE III-45. CREEP TEST DATA, T-111 ANNEALED 1 HOUR AT 3000°F (1649°C) TEST NOS. S48 AND S50, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

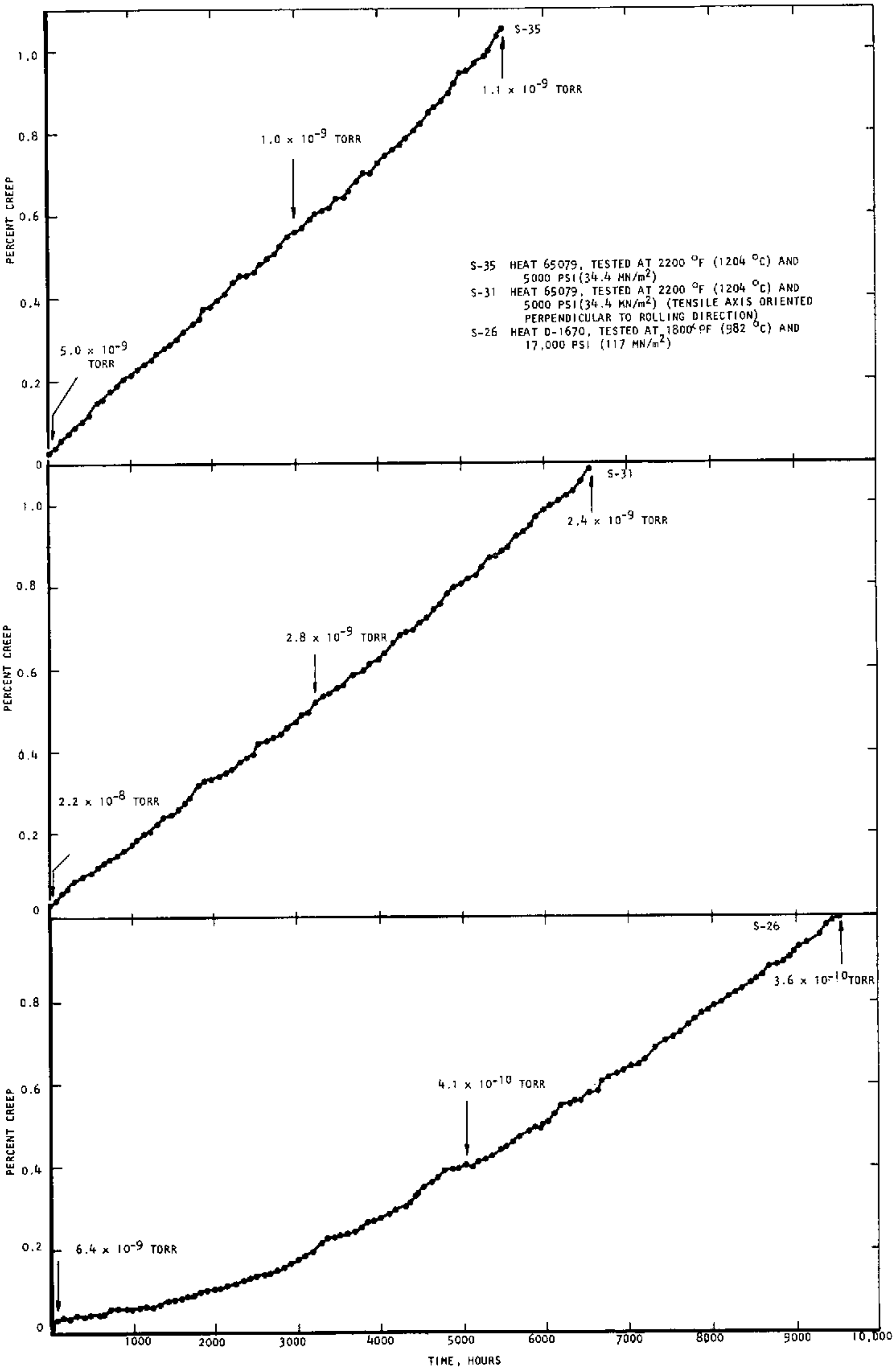

FIGURE III-46. CREEP TEST DATA, T-111 ANNEALED 1 HOUR AT 3000°F (1649°C) TEST NOS. S35, S31 AND S26, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

134 C

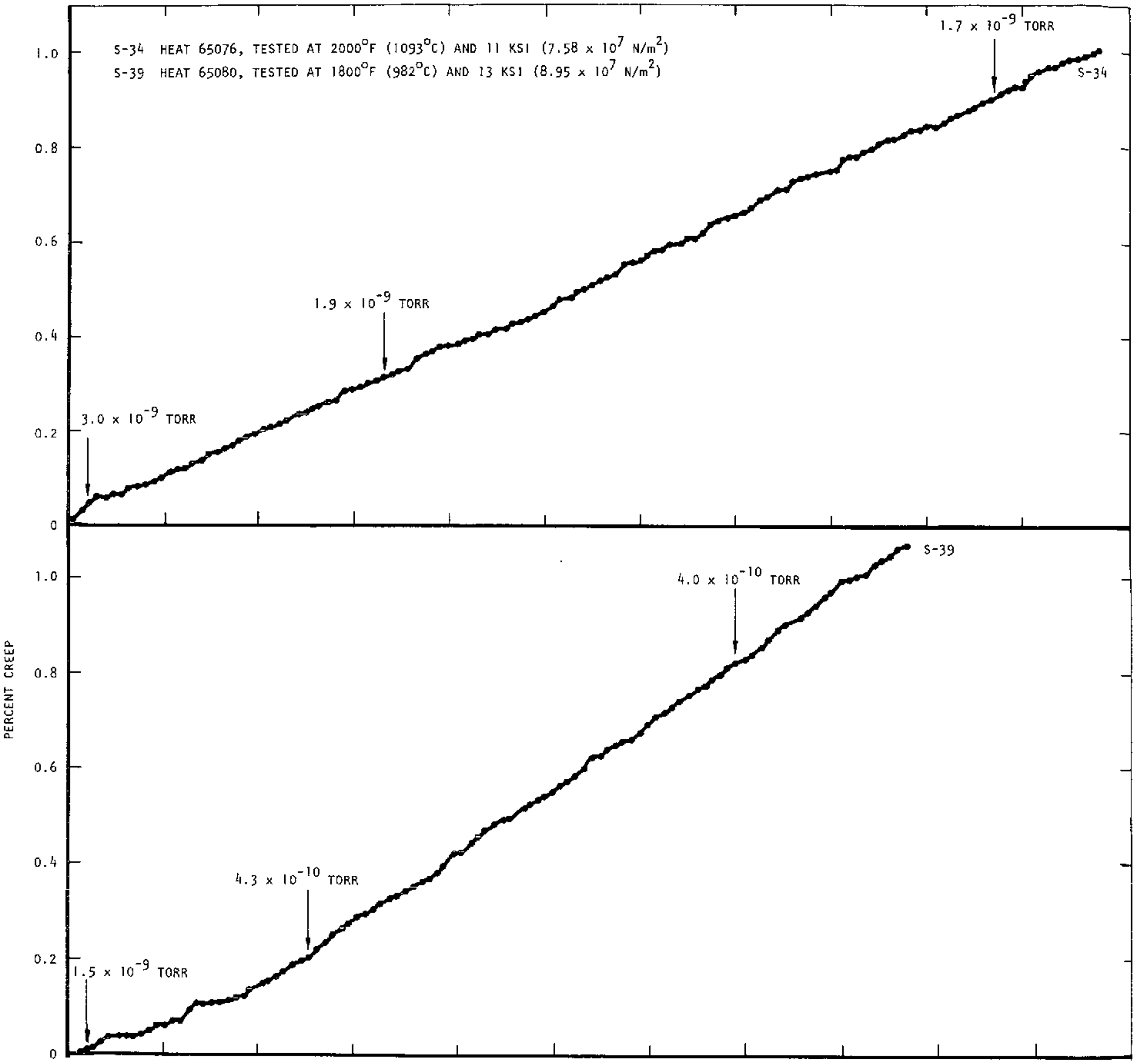

FIGURE III-47. CREEP TEST DATA, T-111 ANNEALED AT 3000°F (1649°C). TEST NOS. S-34 and S-39 TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

2978 B

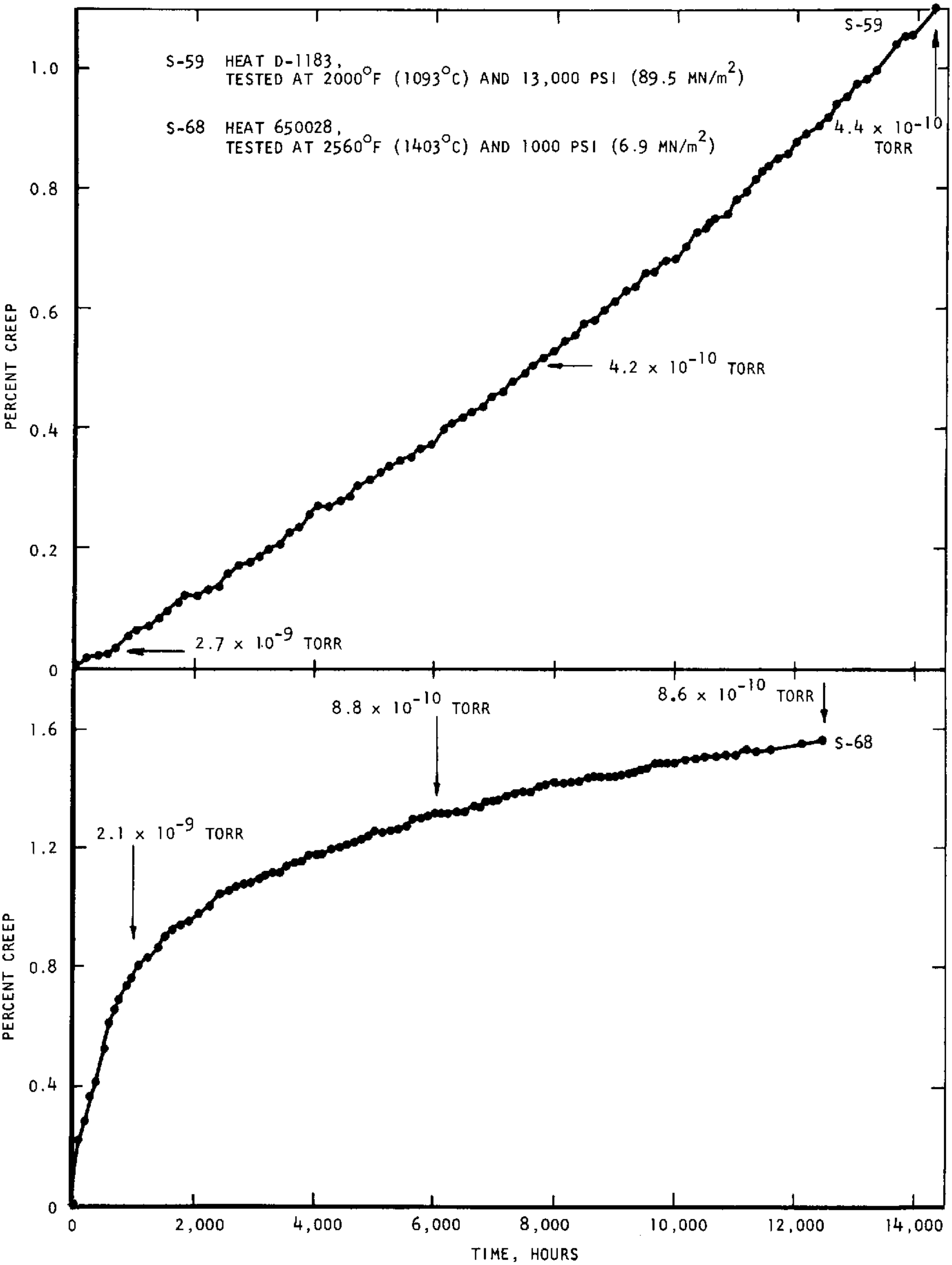

FIGURE III-48. CREEP TEST DATA, T-111, ANNEALED 1 HOUR AT 3000°F (1649°C), TEST NOS. S59 AND S68, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

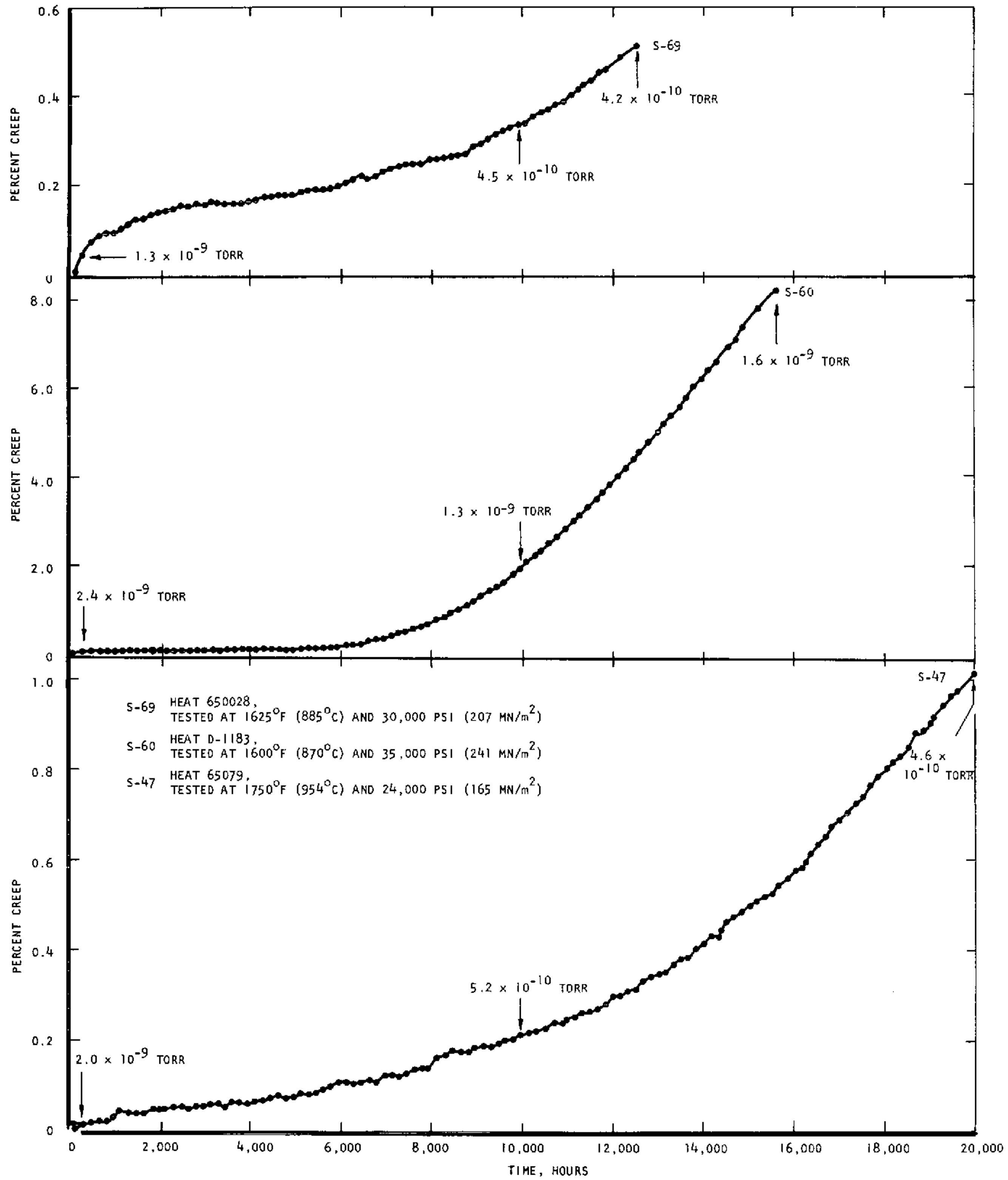

FIGURE III-49. CREEP TEST DATA, T-111, ANNEALED 1 HOUR AT 3000°F (1649°C), TEST NOS. S69, S60, AND S47, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

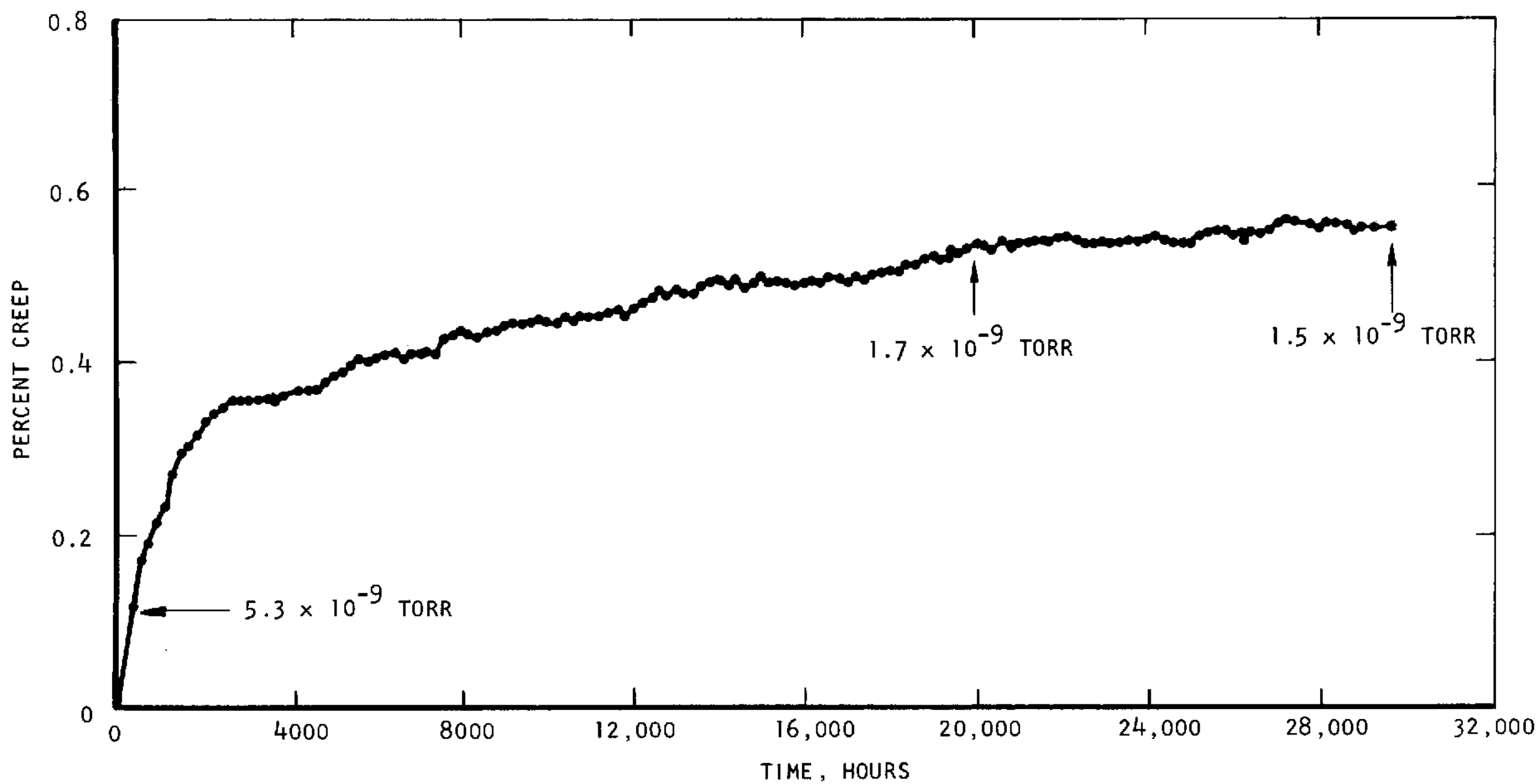

FIGURE III-50. CREEP TEST DATA, T-111 HEAT NO. D-1670 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED AT 2600°F (1427°C) AND 0.5 KSI (3.4 MN/M^2), TEST NO S28, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

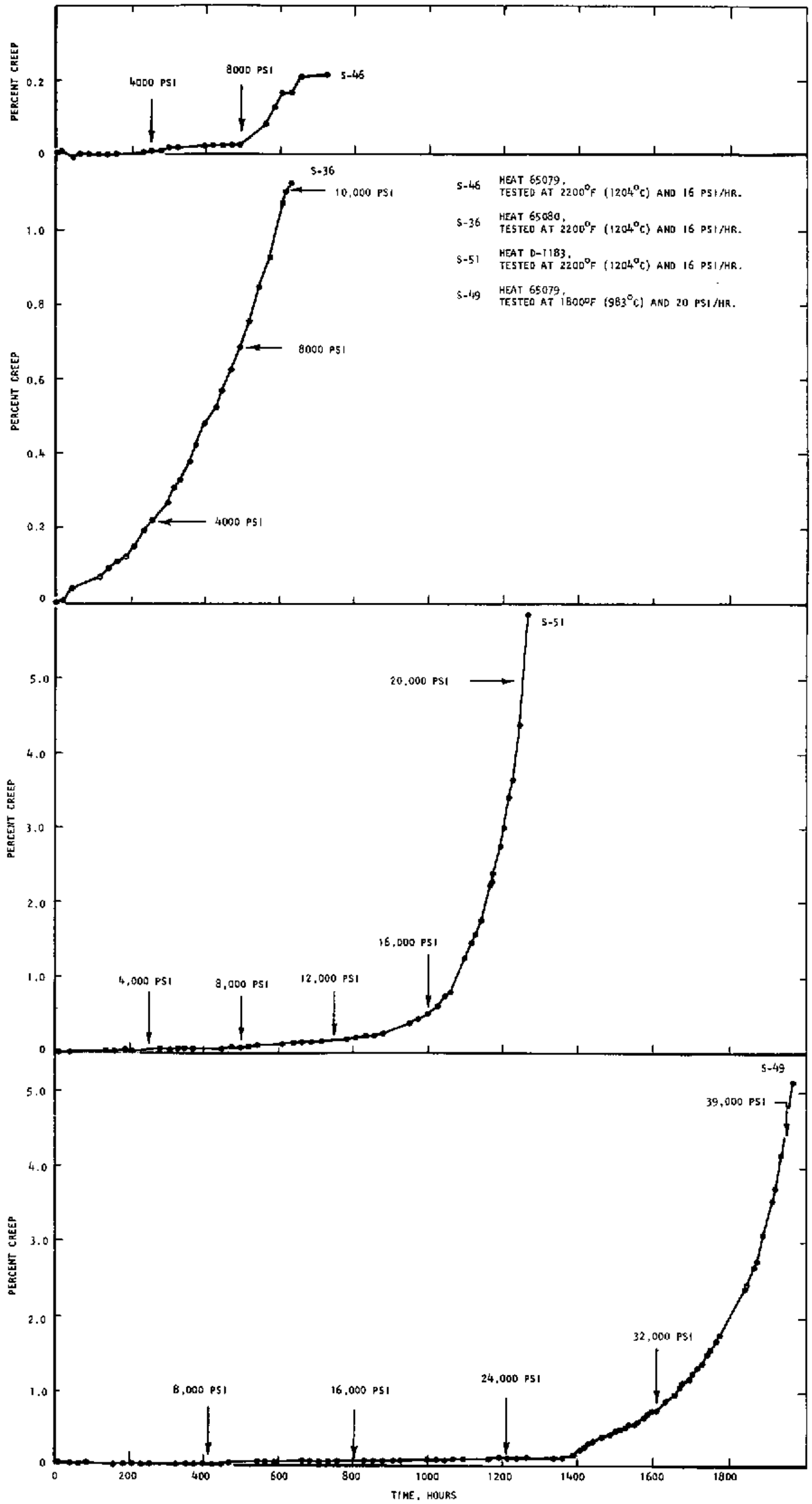

FIGURE III-51. CREEP TEST DATA, T-111 ANNEALED 1 HOUR AT 3000°F (1649°C), TEST NOS. S46, S36, S51 AND S49 IN A VARIABLE STRESS TEST PROGRAM, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE STRESS AT VARIOUS INTERVALS DURING THE TEST.

136 C

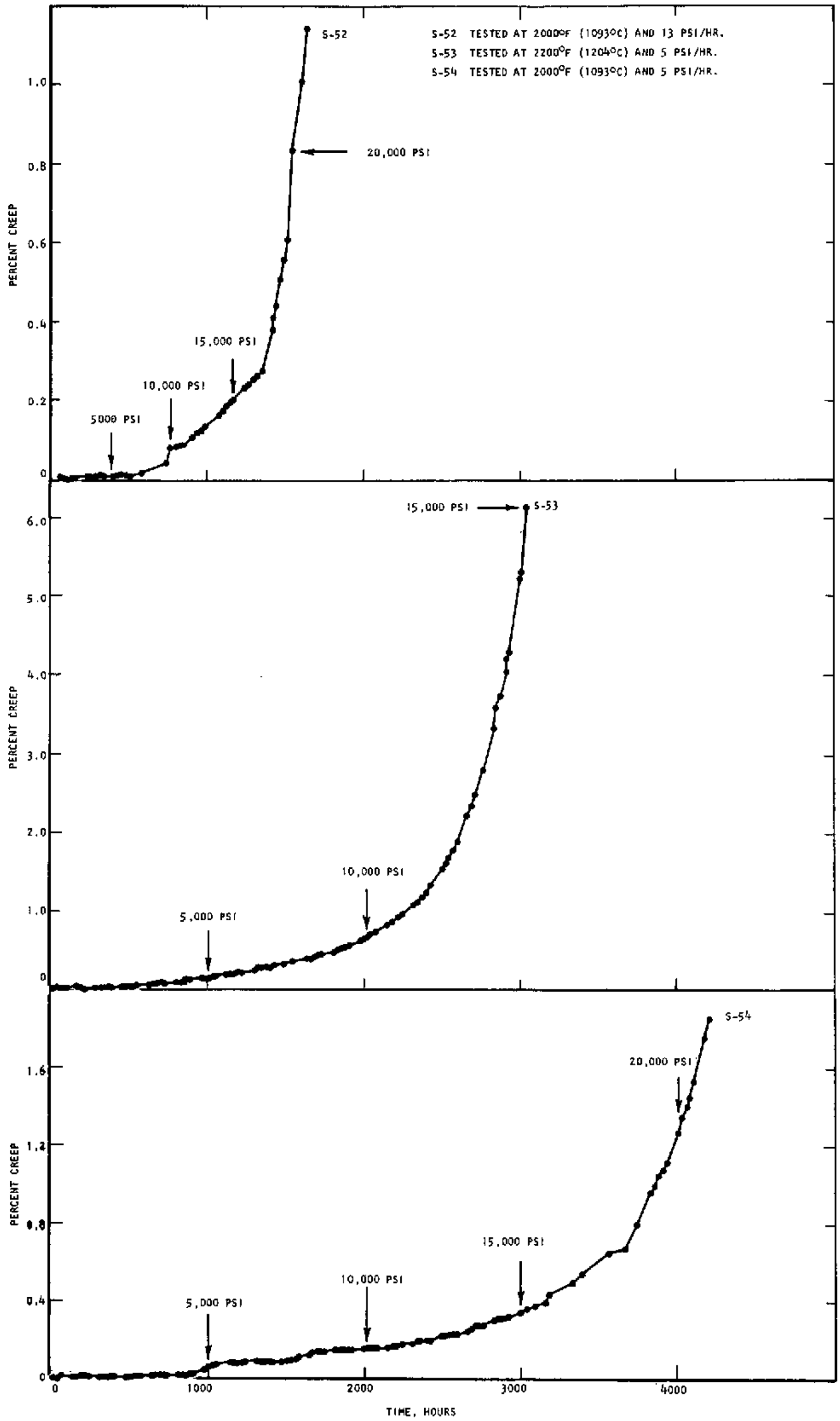

FIGURE III-52. CREEP TEST DATA, T-111 HEAT NO. 65079 ANNEALED 1 HOUR AT 3000°F (1649°C) TEST NOS. S52, S53 AND S54 IN A VARIABLE STRESS TEST PROGRAM, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE STRESS AT VARIOUS INTERVALS DURING THE TEST.

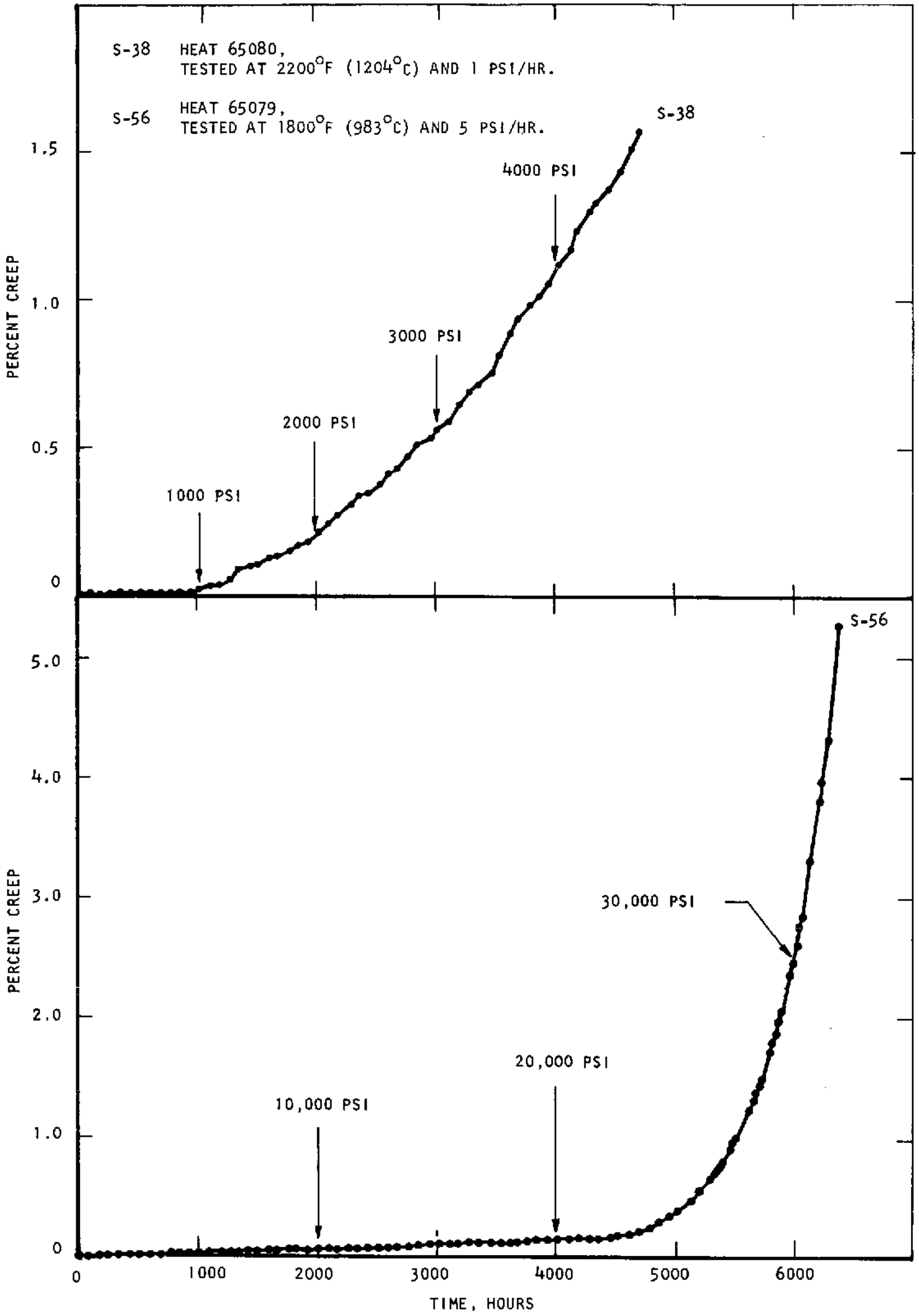

FIGURE III-53. CREEP TEST DATA, T-111 ANNEALED 1 HOUR AT 3000°F (1649°C), TEST NOS. S38 AND S56 IN A VARIABLE STRESS TEST PROGRAM, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE STRESS AT VARIOUS INTERVALS DURING THE TEST.

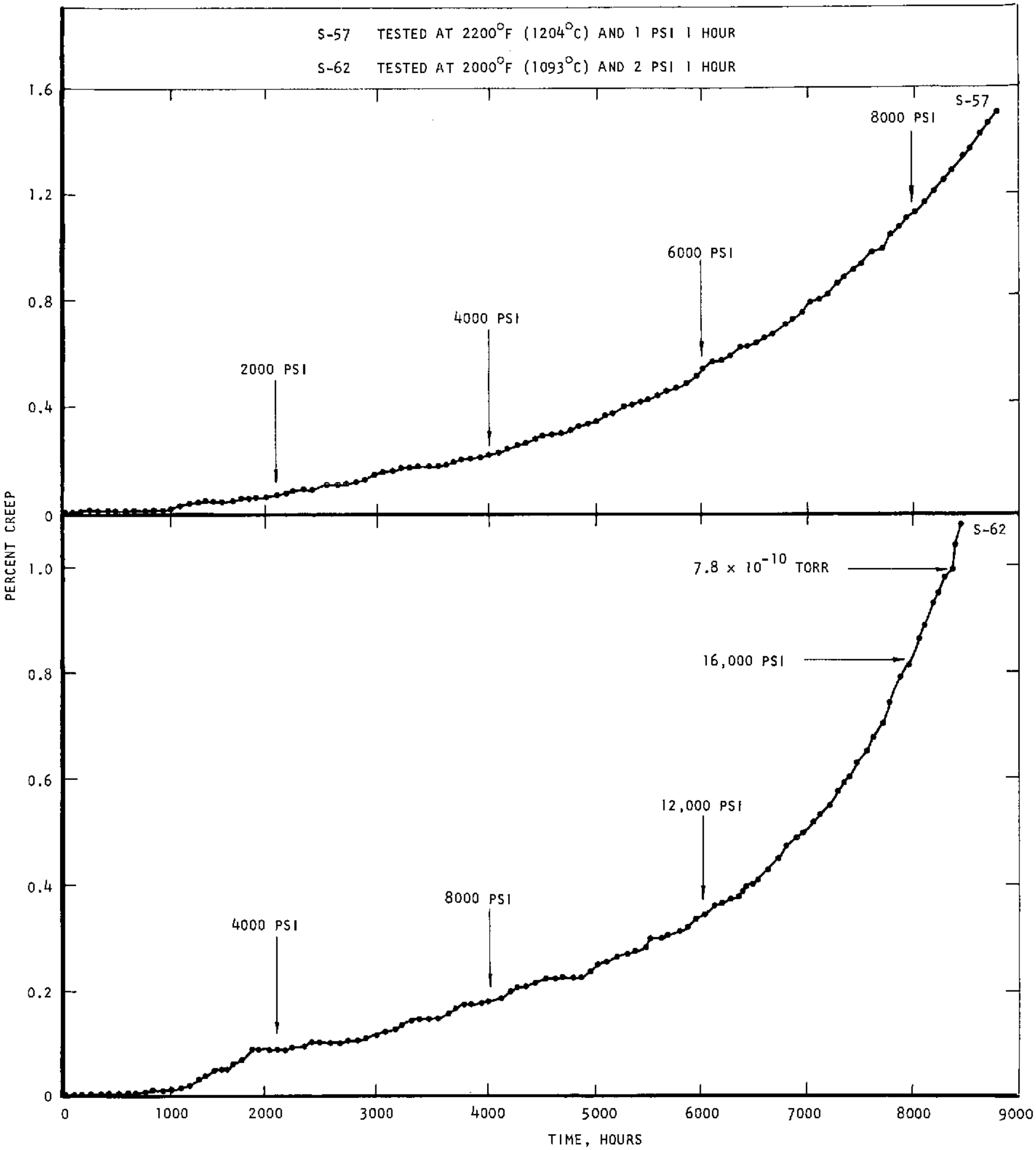

FIGURE III-54. CREEP TEST DATA, T-111, HEAT NO. 65079 ANNEALED 1 HOUR AT 3000°F (1649°C), TEST NOS. S-57 AND S-62 IN THE PROGRESSIVE STRESS PROGRAM, TESTED IN A VACUUM ENVIRONMENT <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE STRESS AT VARIOUS INTERVALS DURING THE TEST.

5273 B

3783 B

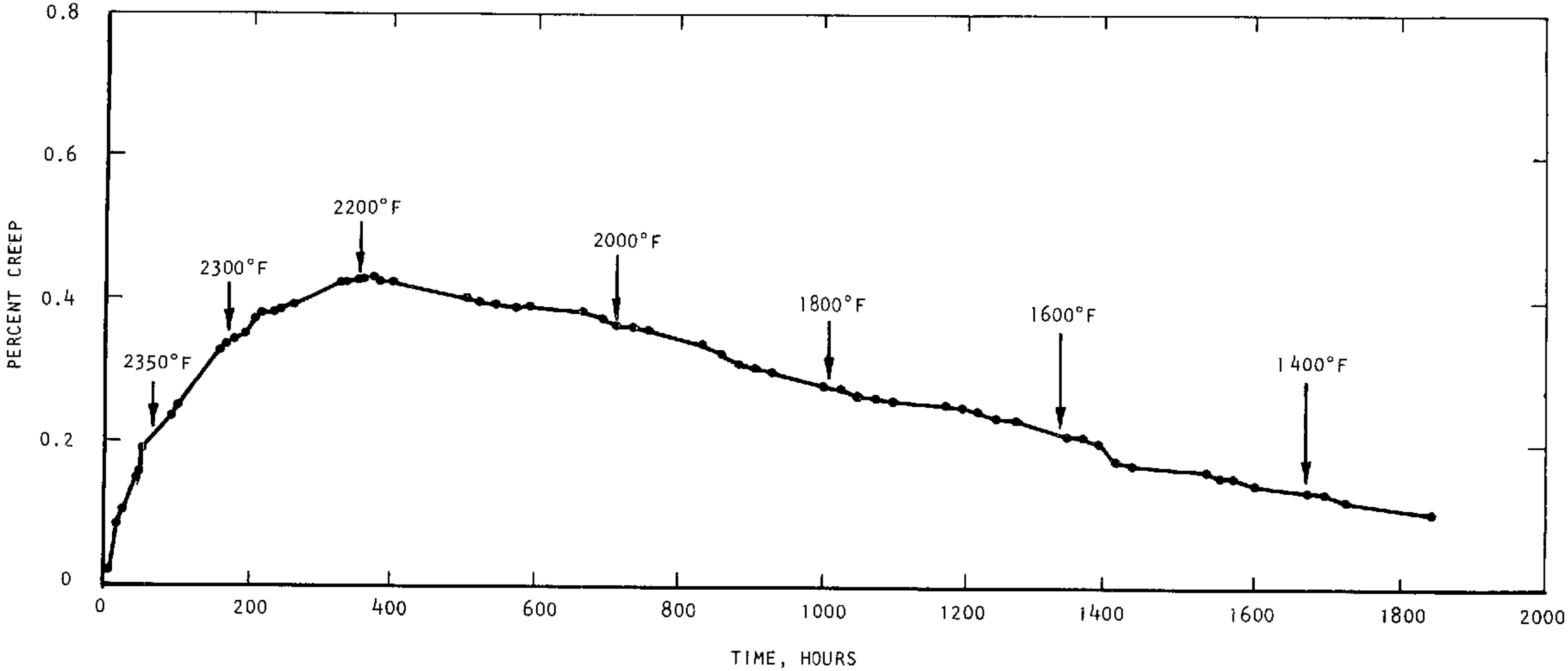

FIGURE III-55. CREEP TEST DATA, T-111 HEAT NO. 65079 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED WITH TEMPERATURE STEADILY DECREASING FROM 2400°F (1316°C) AT 0.6F°/HR., AND AT 7 KSI ($4.82 \times 10^7 N/M^2$), TEST NO. S-65 IN PROGRESSIVE TEMPERATURE PROGRAM, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE TEMPERATURE AT VARIOUS INTERVALS DURING THE TEST.

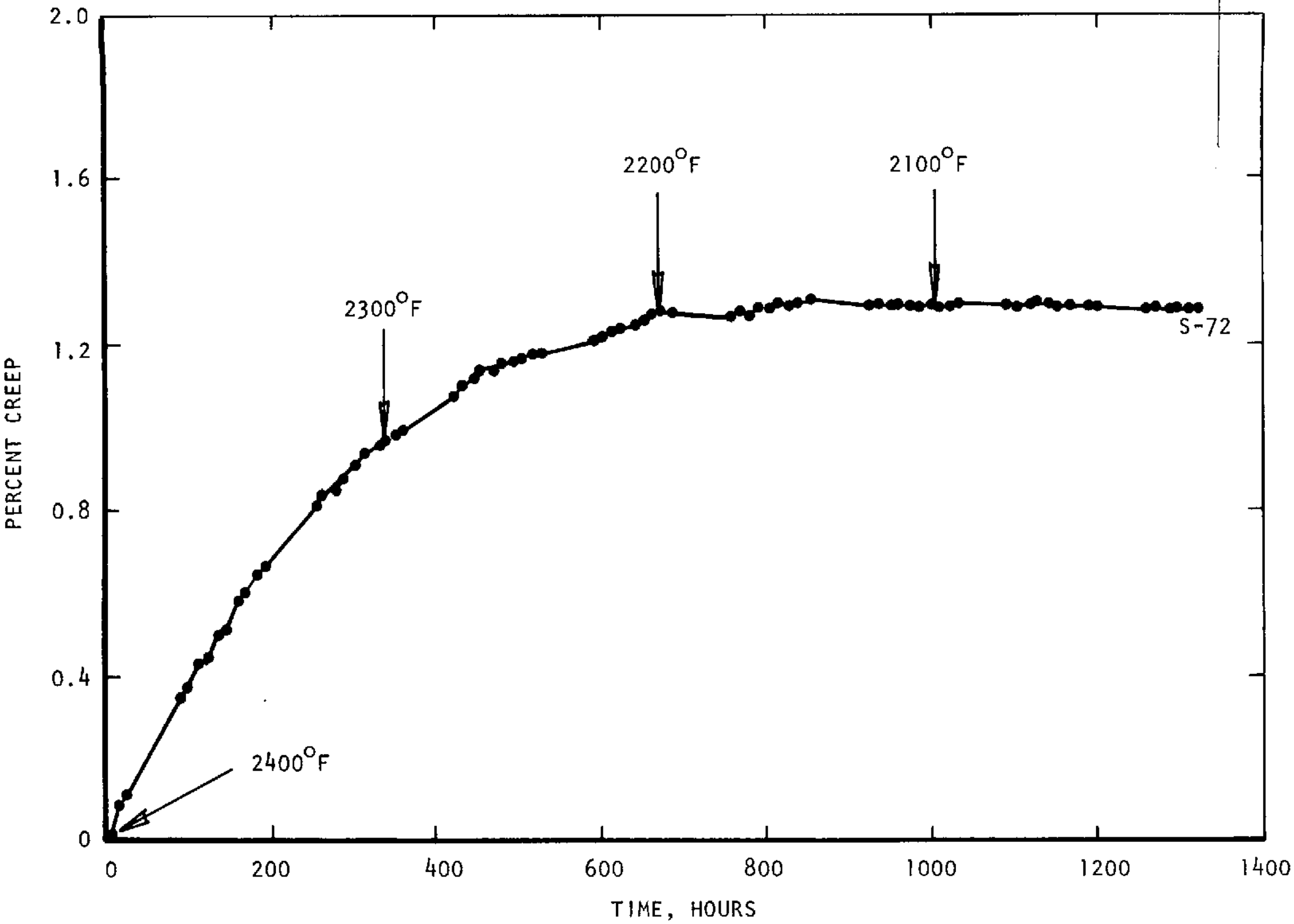

FIGURE III-56. CREEP TEST DATA, T-111 HEAT NO. 650028, ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED STARTING AT 2400°F (1316°C) AND 7 KSI (4.82×10^7 N/m^2), WITH TEMPERATURE DECREASING AT A RATE OF 0.3 F°/HOUR, TEST NO. S-72 IN PROGRESSIVE TEMPERATURE PROGRAM, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVE INDICATE TEMPERATURE AT VARIOUS INTERVALS DURING THE TEST.

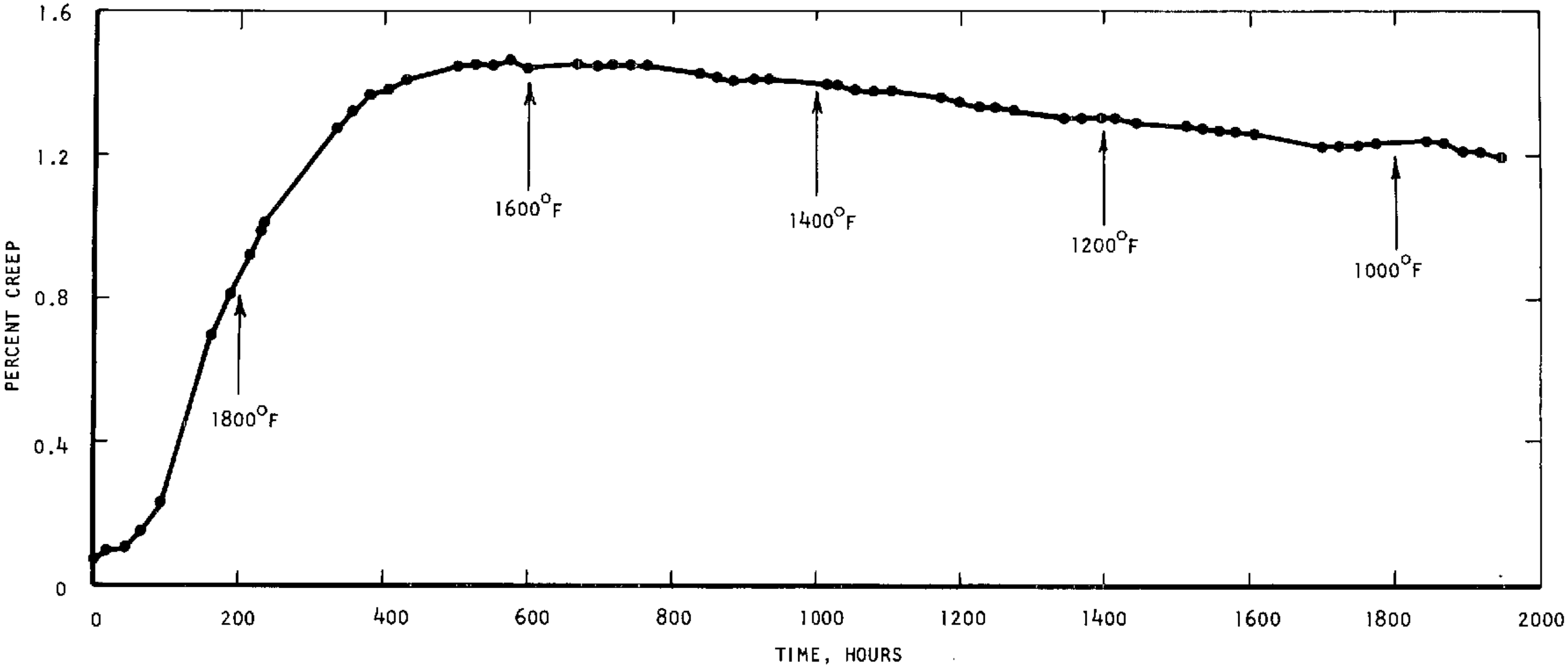

FIGURE III-57. CREEP TEST DATA, T-111, HEAT NO. 650028 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED STARTING AT 1900°F (1038°C) WITH TEMPERATURE CONTINUOUSLY DECREASING AT A RATE OF 0.5°F/HOUR AND AT 31 KSI (214 MN/m^2), TEST NO. S-82, IN THE VARIABLE TEMPERATURE PROGRAM, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE TEMPERATURE AT VARIOUS INTERVALS DURING THE TEST.

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